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POSSIBILITY OF DEFECTS DETECTION BY IR THERMOGRAPHY IN MULTI-LAYERED POLYARAMIDE MATERIALS USED FOR MILITARY APPLICATIONS

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Abstract

Recently the composite materials have been often applied in designs of light ballistic protections as the progress in domain of polymers chemistry has made possible the production of materials providing efficient protection against small arms bullets and fragments. Usually the composites apply textile materials joined with plastic what creates multi-layered composite materials used for personal ballistic protections (vests and helmets for shots and fragments protection) and armours of car vehicles and stationary objects. This type of composite materials is largely made on the basis of very resistant aramid and polyethane fibres joined with phenolic and polyurethane resins and other elastic mixtures. These materials are characterized as lightweight, non-corrosive and easy to form what makes them fit well to the surface, which they have to protect. Defects, which can appear in this type of multi-layered composite materials usually, are inaccuracies in gluing the composite layers and stratifications and delaminations occurring under hits of fragments and bullets. A method that possibly can be used to non-destructive testing of this type of materials and detection of internal defects deploys infrared thermography. In order to determine the potential use of thermal methods the specialized software was developed for computing 3D (three-dimensional) dynamic temperature distributions in anisotropic multi-layered solid body with subsurface defects. The paper includes some results of simulation representing possibilities for the use of IR thermography methods to test such composite materials.

Keywords: *infrared thermography, non-destructive testing, composite material, aramide fabrics, light armours*

1. Introduction

The composite materials are applied more and more often to construction of light ballistic protections. In last years, the progress in domain of polymers chemistry has made possible the production of materials providing efficient protection against small arms bullets and fragments. Most often composites apply textile materials joined with plastic as such binder creates many-layered composite materials used to personal ballistic protections (vests and helmets for shots and fragments protection) and armours of car vehicles and stationary objects. This type of composite materials is largely made on the basis of very resistant aramid and polyethane fibre joined with phenolic and polyurethane resins and other elastic mixtures. These materials are characterized as lightweight, non-corrosive, easy to form what makes them fit well to the surface, which they have to protect. These materials can be also applied in connection with steel sheets and ceramics what increases their efficiency on the protection against bullets and fragments. The damaged composite

armours can be easily replaced by new ones without disassembling of total protection system [1, 2].

Defects, which can appear in this type of many-layered composite materials usually, are inaccuracies in glue of composite layers and stratifications and delaminations occurring under hits of fragments and bullets.

In order to detection of defects in certain material is need of knowledge about thermal parameters these materials, which usually have different values from thermal parameters of defects. Basic thermal parameters of some materials can find in literature. However considering specific of theses material, which is resulting from used different technological processes by manufactures as well as for their utilization (joining) from another materials determination of thermal parameters of final structure of material are necessary.

Knowledge of real thermo-physical parameters is necessary to definition of temperature distributions in numerical analysis as well as in verification results of experimental testing. Adequate definition of thermal parameters of material is basis to proper estimation of differences between thermo-physical parameters of materials and prospecting defects.

Basic thermo-physical parameters of materials are coefficient of thermal conductivity λ, specific heat with constant pressure C_p, density ρ as well as coefficient of thermal diffusivity α.

2. Experimental determination of thermo-physical parameters

Thermal diffusivity of multi-layered aramide composite used in the construction of individual ballistic protective shields was determined experimentally with use of temperature oscillation technique in Faculty of Mechatronics and Aerospace (Military University of Technology). Experimental investigations were made in temperature range from -40℃ to + 100℃. Thermal diffusivity was determined with amplitude and phase data. Obtained data were verification by numerical simulation method.

The investigations of thermal diffusivity were carry out modified Ångström method. The introduced changes resulted with need to carry out measurements in definite range of temperature as well as liquidated limitations connected with necessity of adequate selection of oscillation frequency. Testing two sample of aramide composite perpendicularly and simultaneously to fibres was carry out after control of measuring methods.

The diagram of experimental set-up to measuring thermal diffusivity by temperature oscillation technique is shown in Fig. 1 [3]. Heat insulation of samples has in order to assurance of adiabatic condition. Copper plate adhered to testing sample. Periodical changes of temperature of upper surface of copper plate were generated by use Peltier elements. These elements were supply from direct current power by computer control. Supply voltage was changes with frequency about 1 Hz. Temperature changes (programmable) of bottom surface of copper plate as well as stabilization provided ultra-thermostat. The thermocouples were fixed on opposite surface of sample. Obtained results are shown in Fig. 2.

Measurement of density was executed pycnometer method (used gas pycnometer) in Warefare Agents Testing Laboratory (Military Institute of Armament Technology).

Obtained result of density: 1.45 g/cm^3 = 1450 kg/m^3.

Specific heat was defined relative method used scanning micro calorimeter (DSC) in temperature range from -20°C to +130°C. Obtained results presented in Fig. 3.

3. Modelling thermal NDT of aramide structure

3.1. Mathematical problem

ThermoCalc™-30L computer programme [4] developed by V. Vavilov was used to select suitable heating parameters of the composite material tested sample to provide the detection of subsurface defects. This programme makes possible the investigation of transient phenomena of heat conduction in an object – sample.

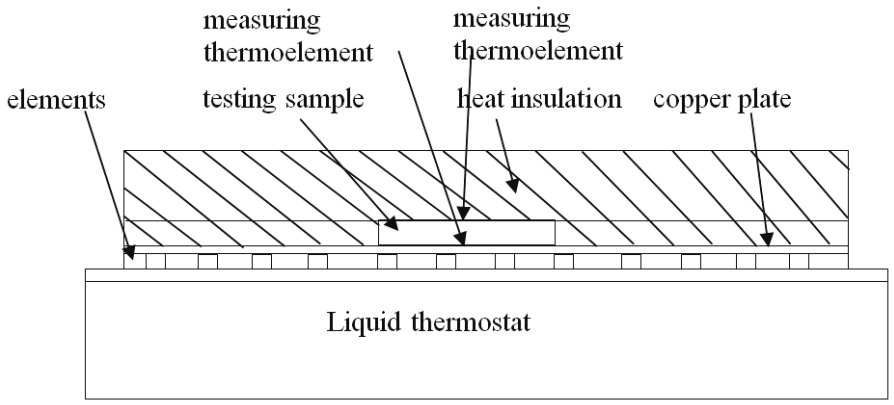

Fig. 1. Diagram of measurement stand of thermal diffusivity by temperature oscillation technique

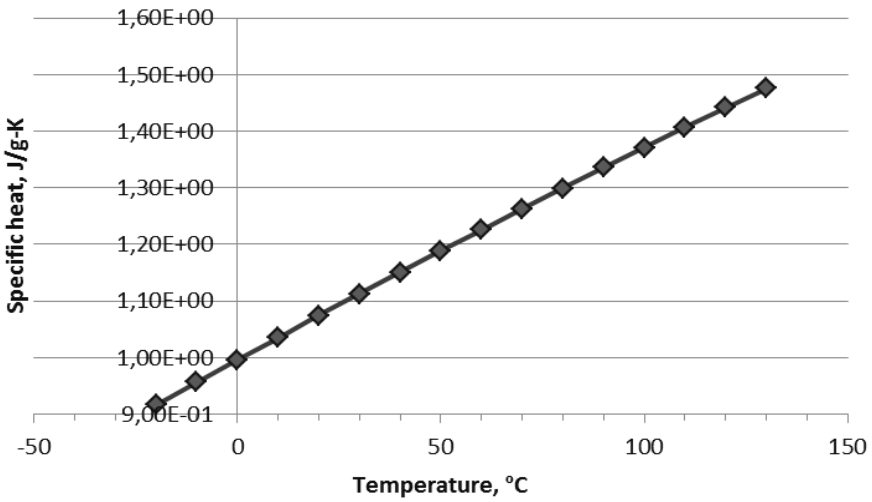

Fig. 2. Graph for representative approximation characteristic of micro calorimetric measure of heat capacity of the test sample

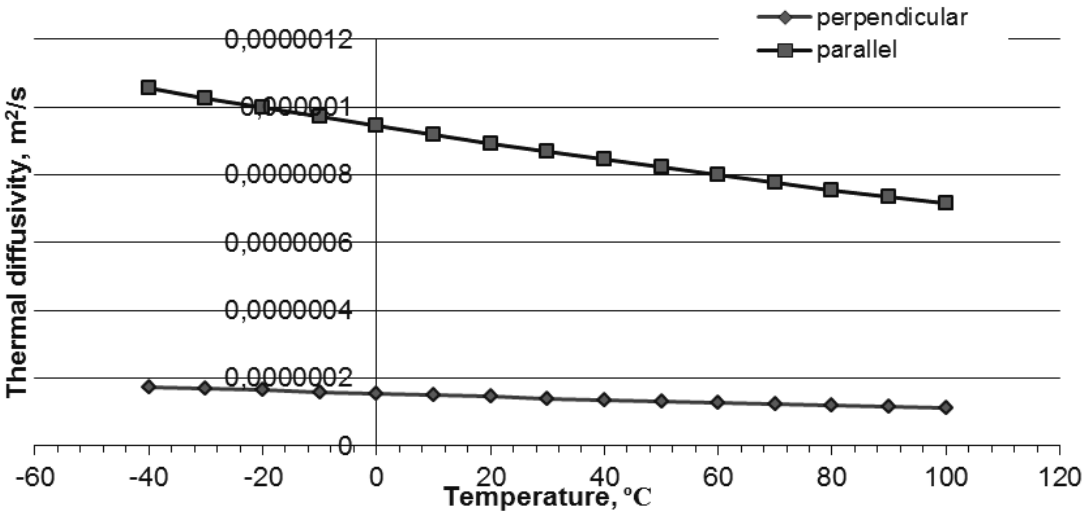

Fig. 3. Graph for representative approximation characteristic of thermal diffusivity of the test sample

Tested object is treated as a solid one placed in the system of Cartesian co-ordinates. In the theoretical model, a sample consists of thirty layers and nine defects and all these elements have shape of parallelepipeds. The heating or cooling is carried out by applying an external heat impulse

on the front surface of the sample. The model assumes that thermal flux on this side is homogeneous or distribution of its density is described by the Gaussian function. In this second case, point of maximum flux density may be located in an arbitrary place of heated surface. In general after the stimulated heating or cooling, front and rear surfaces are subjected to a natural cooling process (and in this process also heat exchange exists in the form of convection and radiation) in accordance with the Newton law. For this purpose, suitable heat exchange coefficients h are introduced. Thermal parameters of a sample and defects can be defined independently in all three planes of space and this makes possible to characterise it as a fully anisotropic one. The model assumes that side surfaces of sample are constantly isolated adiabatically. However, conditions of temperature continuity and transport of heat flux contribute into the heat transportation process between borders of sample layers as well as between defects and their surroundings. In this model, it is assumed to take into account so-called capacitive defects. This is what distinguishes this model from many other practical models in non-destructive testing because in calculations both diffusivity and thermal conductivity of defects are taken into account. Thanks to this, it is possible to get the precise description of physical phenomenon in defect and its surroundings.

Transient processes of thermal conductivity in the object (sample) define areas in the three-dimensional system of Cartesian co-ordinates, which can be described with following system of equations [5]:

– 3D parabolic equation of thermal conduction:

$$\frac{\partial T_i(x,y,z,\tau)}{\partial \tau} = \alpha_i^x \cdot \frac{\partial^2 T_i(x,y,z,\tau)}{\partial x^2} + \alpha_i^y \cdot \frac{\partial^2 T_i(x,y,z,\tau)}{\partial y^2} + \alpha_i^z \cdot \frac{\partial^2 T_i(x,y,z,\tau)}{\partial z^2}, \tag{1}$$

– initial condition of equation:

$$T_i(\tau = 0) = T_{in}, \tag{2}$$

– boundary condition for front surface (heating + cooling):

$$-K_1^z \cdot \frac{\partial T_1(x,y,z=0,\tau)}{\partial z} = Q(x,y,\tau) - h_F \cdot \left[T_1(x,y,z,\tau) - T_{amb}\right], \tag{3}$$

– boundary condition for rear surface (cooling only):

$$K_3^z \cdot \frac{\partial T_3(x,y,z=L_z,\tau)}{\partial z} = -h_R \cdot \left[T_3(x,y,z,\tau) - T_{amb}\right], \tag{4}$$

– adiabatic conditions on the side surfaces by the coordinates x and y:

$$\frac{\partial T_i(x,y,z,\tau)}{\partial x} = 0$$

$$\text{for } x = 0, y = 0 - L_y; x = L_x, y = 0 - L_y, \tag{5}$$

$$\frac{\partial T_i(x,y,z,\tau)}{\partial y} = 0$$

for $y = 0, x = 0 - L_x; y = L_y, x = 0 - L_x$,

– temperature and heat flux continuity conditions on the borders between layers and between layers and defects:

$$T_i(x,y,z,\tau) = T_{i\pm1}(x,y,z,\tau), \tag{6}$$

$$K_i^{q_j} \cdot \frac{\partial T_i(x,y,z,\tau)}{\partial q_j} = K_{i\pm1}^{q_j} \cdot \frac{\partial T_{i\pm1}(x,y,z,\tau)}{\partial q_j},$$

where:

T_i – temperature in the *i*-th region counted from the initial element temperature (i = 1 – 30 corresponds to sample layers, i = 31 – 39 corresponds to nine defects),

T_{in} – initial temperature of sample,

x, y, z – Cartesian coordinates,

q_j – one of Cartesian coordinates *x, y* or *z* (*j* = 1-3),

$\alpha_i^{q_j}$ – thermal diffusivity in the *i* – th region of the coordinate q_j,

$K_i^{q_j}$ – thermal conductivity in the *i* – th region of the coordinate q_j,

τ – time,

$Q(x, y, \tau)$ – heat flux power density, which generally changes in time and space,

h_F – heat exchange coefficient on the front surface,

h_R – heat exchange coefficient on the rear surface;,

T_{amb} – ambient temperature,

L_x, L_y, L_z – sample dimensions.

3.2. The sample to modelling

In order to evaluate a possibility for the use of IR thermography to detect defects in multilayer composite materials constructed on the basis of aramide, the model (Fig. 4) was tested by computer ThermoCalc^{TM}-30L program.

Air-filled defects size 10x10 mm and thickness 0.1 mm were located in following depths: defect D1 – 0.5 mm, defect D2 – 1 mm, defect D3 – 1.5 mm, defect D4 – 2 mm and defect D5 – 3 mm.

Following variants were examined in simulation:

1. The model of a sample was heated on the front surface with a heat pulse. The heating was made with single square pulse. The heat pulse has value power density $Q = 1.5 \cdot 10^5\ W/m^2$ and time of heating $\tau_h = 0.1\ s$. Initial temperature of sample was 20 ºC.
2. The model of a sample was heated on the front surface with a heat pulse. The heating was made with single square pulse. The heat pulse has value power density $Q = 1.5 \cdot 10^4\ W/m^2$ and time of heating $\tau_h = 5\ s$. Initial temperature of sample was 20 ºC.
3. The model of a sample was cooled on the front surface with a cool pulse. The cooling was made with single square pulse. The cool pulse has value power density $Q = 10^4\ W/m^2$ and time of heating $\tau_h = 5\ s$. Initial temperature of sample was 80 ºC.

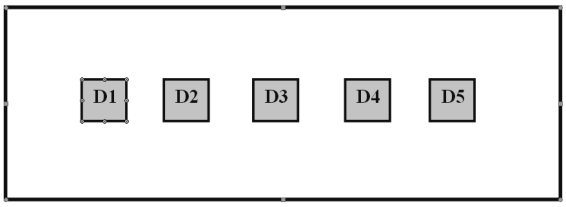

Fig. 4. Location of defects in the model of a sample (size 50x130 mm and thickness 10 mm)

The thermal properties of the materials are assumed as follows:

– aramide – conductivity λ = 0.22 W/(m·K), density ρ = 1450 kg/m^3 , heat capacity C_p = 1070 J/(kg·K),

– air (in thin gaps) – conductivity λ = 0.07 W/(m·K), density ρ = 1.2 kg/m^3 , heat capacity C_p= 1005 J/(kg·K).

3.3. Results

One from option of ThermoCalc-6L^{TM} programme calculates the value of a temperature difference (differential temperature signal) between two selected points.

$$\Delta T(\tau) = T[x_1, y_1, \tau] - T[x_2, y_2, \tau]. \tag{7}$$

This allows analysing optimum observation times for all introduced defects. These periods depend on defect size and depth. The information concerning the temperature difference between point on the front surface of a sample, with being found immediately over a defect and selected point on the surface outside of the defect and time, wherein this difference will be extreme. This is very fundamental for estimation of possibility to use Thermal NDT for testing this type of material.

Another Thermal NDT parameter, of whose extremums can be calculated by the Program, is the running temperature contrast:

$$C(\tau) = \Delta T(\tau) / T[x_2, y_2, \tau]. \tag{8}$$

We assume that a defect can be reliably detected by its surface temperature 'footprint' if the corresponding sample excess temperature T and the signal ΔT meet the following conditions:

- sample maximum excess temperature $T(\tau_h)$ that occurs at the end of heating is lower than the destruction temperature of the sample material T_{destr} (this condition puts a limit onto heat power density and heat pulse duration -100ºC for aramide),
- ΔT signal must exceed a temperature resolution of a used IR system ΔT_{res} (17 mK for camera FLIR SC 7600),
- a running temperature contrast $C = \Delta T(\tau) / T(\tau)$ must exceed the noise level that adheres to each material and surface condition (for example, it is known that even 'black' coatings might reduce noise only up to 2% in terms of the noise running contrast C_n).

In Tab. 1-3 are represented an example of optimum detection parameters for the defects 1-5.

Tab. 1. Expected detection parameters (heating pulse – $Q = 1.5 \cdot 10^5\ W/m^2$, $\tau_h = 0.1\ s$ – variant 1)

Defect	ΔT, ºC	τ_m, s	C, %
1	1.971	1.6	7.8
2	0.542	5.2	5.7
3	0.236	10.3	3.4
4	0.124	16.4	2.5
5	0.014	40	0.1

Tab. 2. Expected detection parameters (heating pulse – $Q = 1.5 \cdot 10^4\ W/m^2$, $\tau_h = 5\ s$ – variant 2)

Defect	ΔT, ºC	τ_m, s	C, %
1	6.513	5	10.4
2	2.4	9	7.3
3	1.151	14	5.3
4	0.642	21	3.7
5	0.085	58	2.1

Tab. 3. Expected detection parameters (cooling pulse – $Q = 10^4\ W/m^2$, $\tau_h = 5\ s$ – variant 3)

Defect	ΔT, ºC	τ_m, s	C, %
1	9.153	7	40.9
2	7.036	8	28.4
3	1.754	15	12.1
4	1.076	22	6.8
5	0.119	100	2.5

If to apply the detection criteria to the data in Tab. 1-3, it can be stated the following:
- the sample maximum surface temperature will not exceed 100 ºC (see Fig. 5),
- the defects 1-5 (variant 1) and all defects 1-6 (variant 2 and 3) produce $\Delta T > 17$ mK,
- the defects 1-5 (variant 1) and all defects 1-6 (variant 2 and 3) produce $C > 2\%$.

Example of calculated thermogram of sample (variant 1) presented Fig. 6 at optimum time for detection of defect D3.

4. Conclusions

Results received from computer simulation showed that composite materials consisted of aramide are difficult material for non-destructive testing by IR thermography but detection of defects in upper layers of composite is possible. Thin air-filled defects could be detected to 3 mm under surface of sample by IR thermography methods (used external heating/cooling pulse).

In further works, we would like to focus on the following objectives:
- use of vibrothermography method with different frequencies of ultrasonic (internal source of heating),
- focus on analysis is more effective algorithms of data which could make possible the detection of defects located on larger depths under surface of composite material.

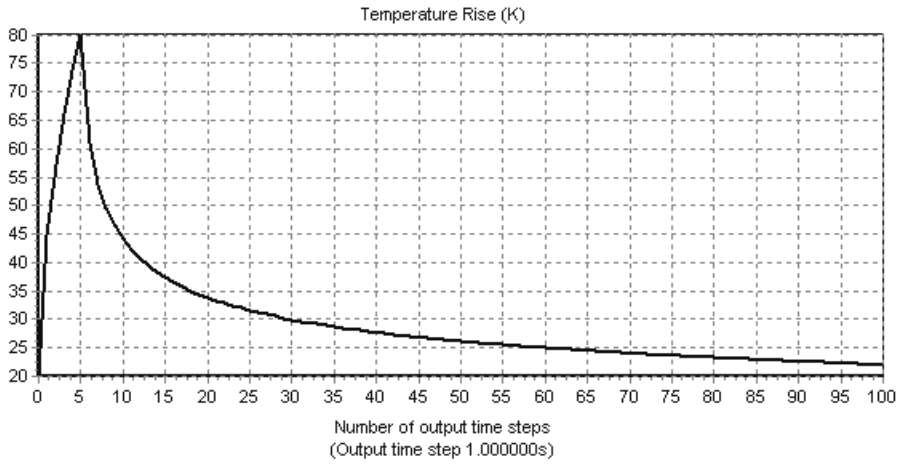

Fig. 5. The surface of sample temperature changes during heating (heating pulse – $Q = 1.5 \cdot 10^4\ W/m^2$, $\tau_h = 5\ s$ – variant 2)

Fig. 6. Appearance of front-surface temperature distribution at optimum time (10.3 s) for detection of defect D3 (heating pulse – $Q = 1.5 \cdot 10^5\ W/m^2$, $\tau_h = 0.1\ s$ – variant 1)

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