

# Possibility of defect detection in multi-layered composite materials used for military applications by IR thermography

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## Abstract

Multi-layered composites are used more often in different military applications as constructional materials and light armours protecting against fragments and bullets. Each layer of these materials has very different physical properties. Therefore they are difficult objects to non-destructive testing and making possible detection of subsurface defects of these materials. Typical defects of composite materials are delaminations, lack of adhesives, condensations and crumpling. 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 six-layered solid body with subsurface defects. In this paper are presented 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 interest with light ballistic protections results from dangers on what troops are exposed participating stabilization-missions. These troops are usually equipped with car vehicles which are exposed against fire from small-calibre weapons and fragments and mines. This demands suitable protection of these vehicles which will assure suitable security level of their crews. 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 are 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 light weight, 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.

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.

So far used method in resistance testing of light ballistic protections was a destructive testing method called the V50 penetration limit velocity and defined as the velocity when the armour is penetrated at 0,5 probability [1]. Taking into account that light ballistic protections have most often the thickness from several to a dozen or so millimeters and they are made from materials whose thermophysical parameters are decidedly different from parameters of potential defects, which can appear in these materials, leads to a conclusion that an efficient method for non-destructive testing

of these materials may be the IR thermography. Therefore in Military Institute of Armament Technology the work was carried out to examine a possibility for use of IR thermography methods for detection of defects in many-layered composite materials applied in light ballistic protections. A first stage of these works was to work out the software to get effective computer simulations for qualification whether the accepted foundation of testing materials by IR methods is right. Results of analyses received by the new and specialized software which provides 3D modeling of the heat flow in many-layered composite materials are presented in the paper.

## 2. Mathematical problem

ThermoCalc – 6L™ computer programme [2] developed by V. Vavilov was used to select suitable heating parameters of the composite material tested sample to provide the detection of subsurface defects. ThermoCalc-6L™ software is a further development of the earlier ThermoCalc-3D™ programme. This programme makes possible the investigation of transient phenomena of heat conduction in an object - 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 six layers and nine defects and all these elements have shape of parallelepipeds (Fig. 1). 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 nondestructive 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.

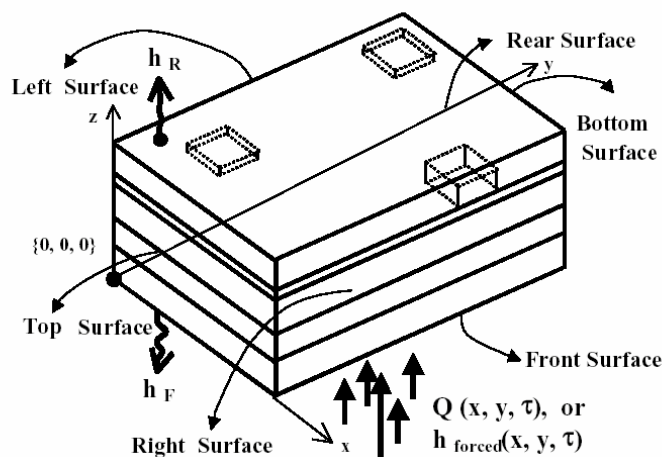


Fig.1. 3D model of sample with subsurface defects

All defects are simulated as parallelepipeds, whose surfaces are properly parallel to surface of border layers and external surfaces of the sample. Defects can be found deep inside layers or appear at point contact with internal border surface whose however they cannot cross. Defects

cannot have point of contact with sample external surfaces neither they can cross these surfaces. According to Fig.1 the sample receives an external thermal stimulus into the front surface.

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 [2,3]:

- 3D parabolic equation of thermal conduction

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

- initial condition of equation

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

- boundary condition for front surface (heating + cooling)

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

- boundary condition for rear surface (cooling only)

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

- adiabatic conditions on the side surfaces by the coordinates x and y

$$\frac{\partial T_i(x, y, z, \tau)}{\partial x} = 0 \quad \text{for } x = 0, y = 0 \div L_y; x = L_x, y = 0 \div L_y \quad (5)$$

$$\frac{\partial T_i(x, y, z, \tau)}{\partial y} = 0 \quad \text{for } y = 0, x = 0 \div L_x; y = L_y, x = 0 \div L_x$$

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

$$T_i(x, y, z, \tau) = T_{i\pm 1}(x, y, z, \tau) \quad (6)$$

$$K_i^{q_j} \cdot \frac{\partial T_i(x, y, z, \tau)}{\partial q_j} = K_{i\pm 1}^{q_j} \cdot \frac{\partial T_{i\pm 1}(x, y, z, \tau)}{\partial q_j}$$

Where:

$T_i$  - temperature in the  $i$ -th region counted from the initial element temperature ( $i = 1 \div 6$  corresponds to sample layers,  $i = 7 \div 15$  corresponds to nine defects);

$T_{in}$  - initial temperature of sample;

$x, y, z$  – Cartesian coordinates;

$q_j$  - one of Cartesian coordinates  $x, y$  or  $z$  ( $j = 1 \div 3$ );

$\alpha_i^{q_j}$  - 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  $q_j$ ;

$\tau$  - 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. The modelling conditions of thermal diagnostic

#### 3.1. The sample to modellig

In order to evaluate a possibility for the use of IR thermography to detect defects in multilayer composite materials constructed on the basis of polyaramide, the model of a 5 – layer structure was tested by computer ThermoCalc-6L™ program. Computer simulation used two kinds of aramide fabrics. In the first of them fibers were interleaved and arranged perpendicularly to themselves (Fig. 2 a) and in the second one they were arranged in parallel (Fig.2 b).

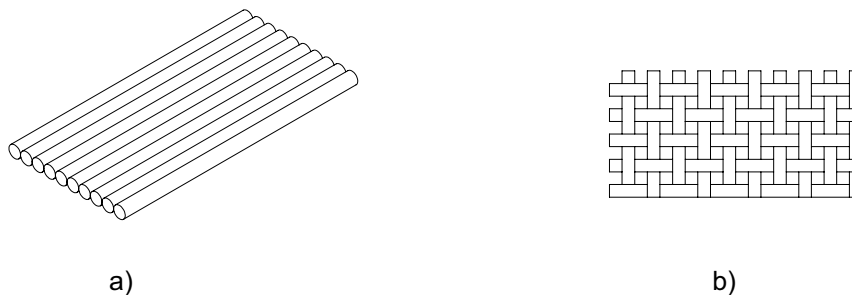


Fig. 2. Strucure of polyaramide fabric

Following variants were examined in simulation:

1. Three layers polyaramide (fibres interleaved perpendicularly) thickness 1 mm every joined by formaldehyde resin two layers thickness 0,5 mm every.
2. Three layers polyaramide (fibres parallels) thickness 1 mm every joined by formaldehyde resin two layers thickness 0,5 mm every. In top and bottom layer of polyaramide direction of fibres configuration was the same but in central layer of sample direction of fibres configuration was perpendicular to top and bottom layer of polyaramide.
3. Three layers polyaramide (fibres interleaved perpendicularly) thickness 1 mm every joined by soft rubber layers thickness 0,5 mm every.
4. Three layers polyaramide (fibres parallels so as in variant 2) thickness 1 mm every joined by formaldehyde resin two layers thickness 0,5 mm every.
5. Two layers polyaramide (fibres interleaved perpendicularly) thickness 1 mm every and bottom layer was sheet steel 1 mm thickness every joined by formaldehyde resin two layers thickness 0,5 mm every.
6. Two layers polyaramide (fibres parallels) thickness 1 mm every, layers of polyaramide were oriented in such way that direction of fibres configuration was perpendicular. The bottom layer was sheet steel 1 mm thickness. These layers were joined by formaldehyde resin two layers thickness 0,5 mm every.

The polyaramide is anisotropic and the sample is non-adiabatic.

The thermal properties of the materials are assumed as follows:  
 polyaramide – conductivity perpendicular to fibers  $\lambda_{\perp} = 0.142 W/(m \cdot K)$ ; conductivity parallel to fibers  $\lambda_{\parallel} = 1.69 W/(m \cdot K)$ ; density  $\rho = 1330 kg/m^3$ ; heat capacity  $C = 1047 J/(kg \cdot K)$ ; diffusivity perpendicular to fibers  $\alpha_{\perp} = 0.1 \cdot 10^{-6} m^2/s$ ; diffusivity parallel to fibers  $\alpha_{\parallel} = 1.19 \cdot 10^{-6} m^2/s$ ;  
 formaldehyde resin - conductivity  $\lambda = 0.2 W/(m \cdot K)$ ; density  $\rho = 1200 kg/m^3$ ; heat capacity  $C = 1850 J/(kg \cdot K)$ ; diffusivity  $\alpha = 2.22 \cdot 10^{-6} m^2/s$ ;  
 soft rubber - conductivity  $\lambda = 0.13 W/(m \cdot K)$ ; density  $\rho = 1100 kg/m^3$ ; heat capacity  $C = 2010 J/(kg \cdot K)$ ; diffusivity  $\alpha = 0.0588 m^2/s$ ;  
 steel – conductivity  $\lambda = 63.9 W/(m \cdot K)$ ; density  $\rho = 7830 kg/m^3$ ; heat capacity  $C = 434 J/(kg \cdot K)$ ; diffusivity  $18.8 m^2/s$ ;  
 air (in thin gaps) - conductivity  $\lambda = 0.07 W/(m \cdot K)$ ; density  $\rho = 1.2 kg/m^3$ ; heat capacity  $C = 1005 J/(kg \cdot K)$ ; diffusivity  $\alpha = 5.8 \cdot 10^{-5} m^2/s$ .

Defects 1-3 (Fig.3) were located in the first layer of resin (rubber), defects 4-6 were located in the second layer of resin (rubber). Air-filled defects size 5x5 mm had following thicknesses: defects 1 and 4 – 0.1 mm; defects 2 and 5 – 0.2 mm; defects 3 and 6 – 0.5 mm.

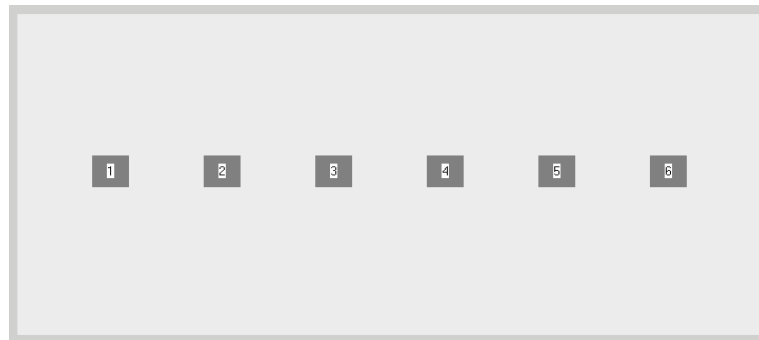


Fig. 3. Location of defects in the model of a sample (size 50x100 mm)

The model of a sample was heated on the front surface with a heat pulse. The heating was made with two kinds of square pulses. The first has value power density  $Q = 10^5 W/m^2$  and time of heating  $\tau_h = 0.1 s$  and for the second value power density  $Q = 10^4 W/m^2$  and time of heating  $\tau_h = 5 s$ .

### 3.2. Results

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

$$\Delta T(\tau) = T[x_1, y_1, \tau] - T[x_2, y_2, \tau] \quad (7)$$

This allows to analyze optimum observation time periods 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 constant:

$$C(\tau) = \Delta T(\tau) / T[x_2, y_2, \tau] \quad (8)$$

In all examined variants defects located in the first layer of resin (rubber) were detected. Only defects in the first layer were detected for the flash heating with power density  $Q = 10^5 \text{ W/m}^2$  and time of heating  $\tau_h = 0.1 \text{ s}$ . For the second value of heating ( $Q = 10^4 \text{ W/m}^2$  and  $\tau_h = 5 \text{ s}$ ) defects in second layer of resin (rubber) were also detected. Defect about 0.5 mm thickness was detected in all variants but defect with 0.2 mm thickness was not detected in the 4 variant. Only defect with 0.1 mm thickness (second layer of resin) was not detected in any variants.

Optimum observation time for variant ( $Q = 10^5 \text{ W/m}^2$  and  $\tau_h = 0.1 \text{ s}$ ) was from 4.7 s to 6.6 s. For variant ( $Q = 10^4 \text{ W/m}^2$  and  $\tau_h = 5 \text{ s}$ ) was from 7.9 s to 10 s (first layer) and from 24 s to 35 s (second layer).

The front surface of sample was heated up to maximum 70°C.

In Table 1 is represented a example of optimum detection parameters for the defects 1-6 (variant 1).

Table 1

Expected detection parameters ( $Q = 10^4 \text{ W/m}^2, \tau_h = 5 \text{ s}$  - variant 1)

Defect	$\Delta T, ^\circ\text{C}$	$\tau_m, \text{s}$	C, %
1	0.847	8.5	4.9
2	1.457	8.8	6.3
3	2.528	9.5	9.0
4	0.046	24.7	1.1
5	0.109	25.7	2.2
6	0.169	27.8	2.9

#### 4. Conclusion

Results received from computer simulation showed that composite materials consisted of polyaramide are difficult material for nondestructive testing by IR thermography but detection of defects in upper layers of composite is possible. Experimental testing is planned in the future for confirmation of executed computer simulation.

#### 5. Acknowledgments

This work was supported by the State Committee for Scientific Research

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