NONDESRUCTIVE TESTING OF COMPOSITE MATERIALS FOR MILITARY APPLICATIONS BY IR THERMOGRAPHY METHODS

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1. INTRODUCTION

Non-destructive testing methods are used to detecting defects in materials and evaluation of materials properties without causing changes to their usable properties. They are applied in diagnostics and industry to provide the assurance of high quality for semi-manufactured products, final products, devices and construction. Except of many civilian applications they are widely used in rocket and aviation industry and also in many special military areas. Typical technical objects of non-destructive testing are different kinds of connections of materials (welded and soldered and glue joints etc.) as well as constructions and elements made from composite materials.
Composite materials are often more practical to be used for different military applications. These interesting materials are effective especially through their good strength properties, corrosion resistance and low specific weight. These materials have various structures. Any damage of these materials usually has a more complicated and other form than in metals and that is why methods and diagnostic techniques checked in metal constructions are often deceptive in constructions made from composite materials. The infrared thermography non-destructive testing methods prove to meet the expectations well in composite constructions. The main centre in Poland for research and development work on infrared thermography non-destructive methods is the Military Institute of Armament Technology (MIAT) where work is carried out for three groups of composite materials used in following areas: aviation, light ballistic protections and ammunition.
Aviation constructions with cellular filling structures are subjected to the risk of water penetration in the case of superficial discontinuities and lack of tightness. Due to flights at high altitudes and differences of temperatures and pressures, the water freezes causing delamination of the cover from the cellular filling material of these structures. This may affect the safety of flight. Even microscopic discontinuities of the material can cause the penetration of the water inside composite structures. They may be difficult to detect by non-destructive testing but the presence of moisture inside the composite structure creates a potential risk for defects. The fast detection of micro-defects can permit to avoid unexpected defects of aerospace elements. It means that detecting even small quantities of water inside a composite is essential.
The light ballistic protections are different type of composite materials which are tested by nondestructive IR thermography methods. Defects of light ballistic protections could be in result of hitting or firing. Different types of defects could be formed in process of production or in result of long-live use.
Defects in composite pyrotechnic materials and products can happen in production stage as well as in service time esp. during long-term storage. The diverse, changeable environmental conditions lasting in life cycles of pyrotechnic materials and products decide in considerably degree about their physicochemical characteristics such as thermal, mechanical parameters, stability, material compatibility and durability. In the paper both computer simulations to define defects which could be detected using IR thermography method and selected experimental investigations are presented as well.
The aim of nondestructive testing by IR thermography is the qualification of object properties during temporary processes occurred at cyclic or impulse thermal stimulation of a testing object such as heating or cooling. As an available form of answer on thermal stimulation is change of temperature and speed of temperature changes it contains information about values of capacity and thermal conductivity, characterising internal structure of a testing object. The basic foundation of nondestructive testing methods with IR thermography technics is fact that every class of testing

objects reacts on stimulation in a specific manner. There can be different reactions of using stimulation of a particular type to cause the beginning of thermal wave and reaction of an object against its spreading. As stimulation can be used:

- sound waves,
- infrared lamps,
- microwaves,
- flash lamps,
- lasers,
- other.

The stimulation has most often the character of an impulse or sinusoidal wave. The answer of an object against stimulation is registered by the thermal system and next on the base of thermograms analyses result images with visible defects are given.

A lot of methods of nondestructive testing by IR thermography are well-known and in practical use. The most from them are described on the work of X. P. V. Maldague [1].

In Military Institute of Armament Technology the most often used methods for composite testing are:

- optical lock-in thermography,
- reflection method,
- transmission method,
- active method with microwave source.

The paper contains a short review of the current and planned research work on the above mentioned subjects in MIAT.

2. COMPOSITE MATERIALS IN AIRCRAFT INDUSTRY

The honeycomb type composites are one of basic materials used in aircraft constructions from many years. These materials possess many advantages like the low weight at great mechanical resistance. Thanks to its excellent flexural stiffness and large corrosion resistance honeycomb composite materials are commonly used in aircraft industry. They are also used in many other applications [2]. A basic element in this type material is a 3-dimensional core structure with hexagonal cells reminding the honeycomb (Fig.1). Both sides of the core are covered by thin layers made usually from a different kind of material than core. Defects in honeycomb materials are different than defects in metals and for that reason classic evaluation methods can be less effective to detecting defects and flaws. Typical defects of honeycomb materials are cracks and microcracks and dents of covering, separation of covering from the core as well as flaws in sides of cells in the core.

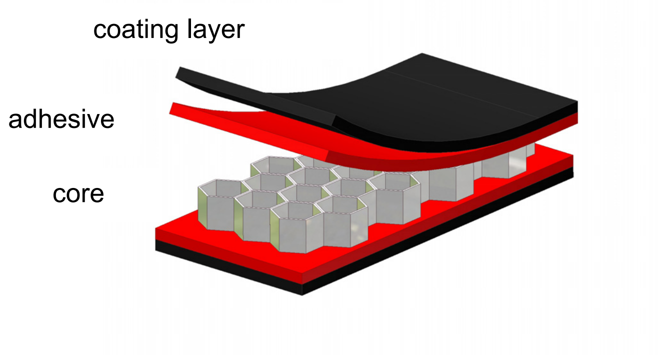


Figure 1. Structure of honeycomb composite material

In aviation applications the detection of water and sogginess is very essential. Their occurrence is witnessed by the existence of cracks and microcracks through which water or steam can penetrate

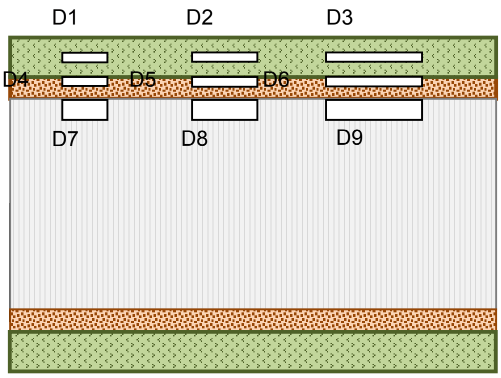
into the material at large differences of pressure and temperature occurring in a short time. Detection of inside defects in composite materials is provided by different non-destructive testing methods which permit to monitor state of construction and do not have any permanent influence into the status of these materials. A type of non-destructive testing is the active IR thermography.
IR thermography is a nondestructive, non-contact and non-intrusive mapping of thermal patterns on the surface of objects. Defect detection principle in active thermography is based on the fact that a difference in thermal properties exists between the sound (non-defective) area and a defective region and it can be used for defect detection and quantification purposes.

2.1. Computer simulations

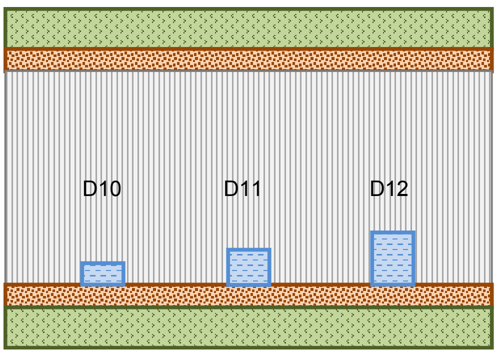
The results of computer simulations and tests on detecting different types of defects in aircraft components made from honeycomb materials are presented in the paper [3]. In order to evaluate a possibility for the use of IR thermography to detect defects in honeycomb composite materials a specialized computer ThermoCalc-6L^{TM} program was used [4].
The structure to be analyzed can be naturally simulated by models (Fig. 2). Computer simulation used two kinds of honeycomb composite materials. The first of them consists of the core from aluminium (hexagonal cell size 25.4 mm) covered with graphite-epoxy fabric (0.635 mm-thick) joined with the core by formaldehyde resin glue (0.3 mm-thick) and in the second one it was the only change in replacing the covering fabric by the aluminum sheet. All dimension are just the same. The size of the surface models was 20x30 mm. Defects in Model 1 (Fig. 2) were simulated by air gaps: Defects 1÷3 – delamination inside of covering layer (only for graphite-epoxy fabric), Defects 4÷6 – delamination between the core and covering layer, Defects 7÷9 – damage of cells in the core. Defects 10÷12 in Model 2 (Fig. 2) different quantities of water in the cells of the core (1 ml, 2 ml and 5 ml) were simulated. All samples were subjected to front surface tests (τ_h-heat pulse duration; Q-heat power density). Heating by a heat pulse was described by the Gaussian function with the pulse center being placed at the center of sample.

$$Q = Q_m \exp\ [-\sigma_x(x-x_0)^2 - \sigma_y(y-y_0)^2] \qquad (1)$$

The coefficients σ_x and σ_y define the localization of the heat source.



Model 1



Model 2

Figure 2. Models

The Table 1 shows thermal properties of the materials used in the computer simulation.

TABLE 1. THERMAL PROPERTIES OF MATERIALS

Material	Specific heat (kJ/kgK)	Conductivity (W/mK)	Density (kg/m^3)
Graphite-epoxy	935		1400
direction (‖)		11.1	
direction (⊥)		0.87	
Aluminium	875	177	2770
Core*	987	3.25	51
Formaldehyde resin	1150	0.25	1200
Water	4193	0.586	1000
Air (thin gaps)	1005	0.07	1.2

* Thermal properties of the core (consist of aluminum cells – 1.8% of the core, filling up air – 98.2% of the core) were given with the following formula:

$$k_{Core} = k_{Al} \cdot 0.018 + k_{Air} \cdot 0.982 \qquad (2)$$

where k_{Al} and k_{Air} are thermal properties of aluminum and air respectively.

The optimum detection conditions (τ_h = 0.01 s) for detecting 1÷12 defects in simulated samples are presented in Table 2. The values of *maximum contrast* - C_m and *temperature signal* - ΔT_m are presented along with their optimum observation times - τ_m. These values can serve as references when analyzing different algorithms in Thermal NDT.
It is assumed that a defect can be reliably detected by its surface temperature 'footprint' if the signal ΔT meets the following conditions:

- a ΔT signal must exceed a temperature resolution of a used IR system ΔT_{res};
- a running temperature contrast $C = \Delta T(\tau) / T(\tau)$ must exceed the noise level that adheres to each material and surface conditions (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).

Let's assume that $\Delta T_{res} = 0.1^o C$ and $C_n = 2\%$. Applying the detection criteria to the data in Table 2 the following can be stated:

- all defects 1-12 produce $\Delta T > 0.1^o C$;
- all defects 1-12 produce $C > 2\%$.

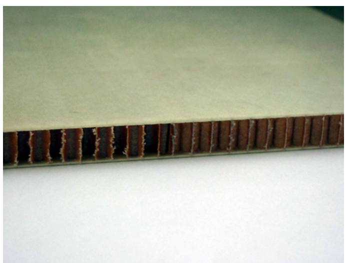
2.2. Experimental investigation

In paper [5] we introduced the use of several methods of infrared thermography to find out which of them is more effective for detection of sogginess in composite materials of honeycomb type. In comparative research we used four methods: optical lock - in thermography, reflection method, transmission method and active method with microwaves source. In all these methods we used thermal camera AGEMA 900 LW to record the results. To identify the areas in composite material which contain the water it was used a prepared suitable test-sample which was a 290x215 mm sized sandwich panel with two 0.7 mm thickness fiberdux face skins. Between covers a honeycomb core with height 12.8 mm with areoweb was placed. Covers with the core were joined by an epoxy resin. Different content of water (5.0 ml, 2.5 ml, 1.2 ml and below 1 ml) were introduced in the sample to four cells. Selected results is shown in Fig. 3.
In the aerospace industry, there is a bunch of NDE solutions for characterization of composite integrity. A type of materials, component design and peculiarities of access to inspected components decide about the choice of proper NDE techniques. In paper [6], some approaches to the detection of disbonds, delaminations and foreign object inclusions have been analyzed. In particular, three NDE techniques have been explored, namely ultrasonics, IR thermography and X-

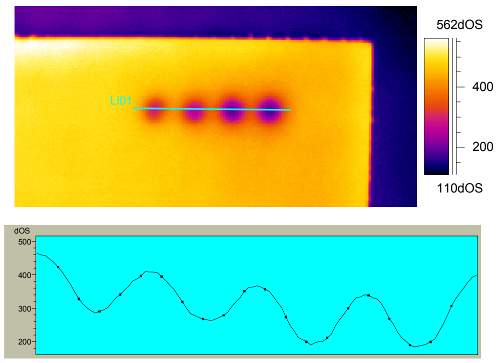
ray radiography. Fig. 4 presents example of experimental results obtained by infrared thermography method.

TABLE 2. RESULTS OF SIMULATION

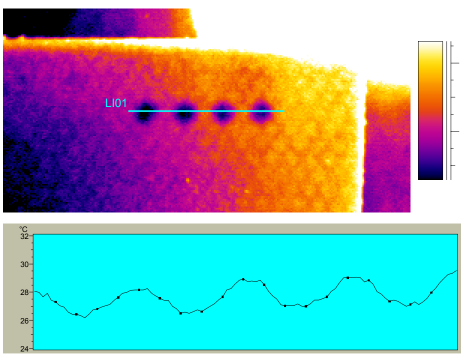
Model No	Defect No	C_m	τ_m (s)	ΔT_m (°C)	Size defect (mm)	Depth defect (mm)	Q_{max} x10 ^{5} kW/m^2
Model1 covered g-e	1	0.860	0.3	1.366	10x10x0.1	0.3	2
	2	0.777	0.35	1.669	20x20x0.1	0.3	
	3	0.544	0.35	-1.945	30x30x0.1	0.3	
	4	0.348	1.0	1.086	10x10x0.1	0.64	
	5	0.342	1.0	0.404	20x20x0.1	0.64	
	6	0.170	1.0	-1.961	30x30x0.1	0.64	
	7	0.218	1.0	1.086	10x10x1.0	1.0	
	8	0.237	1.0	0.276	20x20x1.0	1.0	
	9	0.122	0.01	-1.965	30x30x1.0	1.0	
Model2 covered g-e	10	-0.046	1.72	-0.157	1 ml	20	
	11	-0.089	2	-0.206	2 ml	20	
	12	-0.226	2	-0.368	5 ml	20	
Model1 covered alum.	4	0.158	0.09	1.264	10x10x0.1	0.64	20
	5	0.126	1	1.196	20x20x0.1	0.64	
	6	-0.105	0.01	-1.359	30x30x0.1	0.64	
	7	0.126	1	0.877	10x10x1.0	1.0	
	8	0.163	1	1.123	20x20x1.0	1.0	
	9	-0.122	0.01	-1.583	30x30x1.0	1.0	
Model2 covered alum.	10	-0.074	0.82	-0.110	1 ml	20	
	11	-0.140	1.04	-0.227	2 ml	20	
	12	-0.349	1.61	-0.687	5 ml	20	



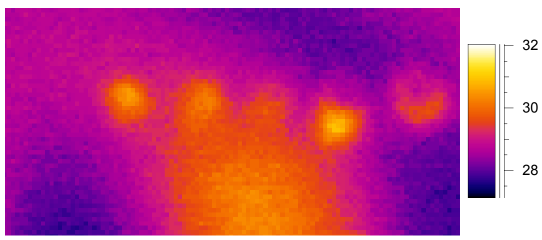
a) Photography of test sample



b) Lock-in amplitude image and profile plots of cells containing water, f = 0,039Hz

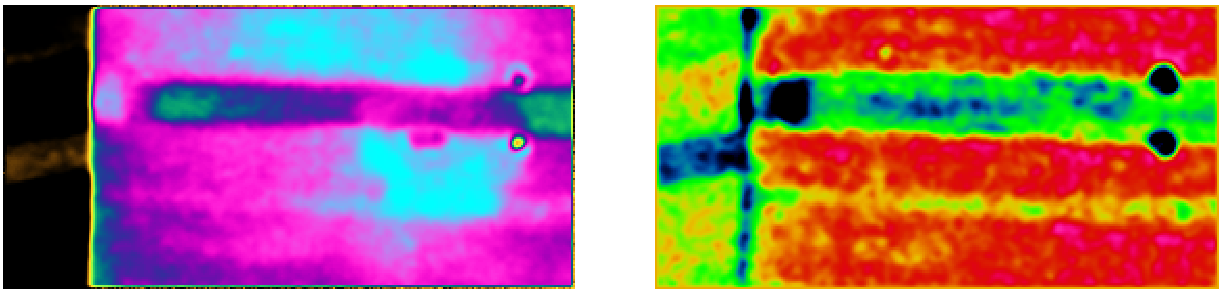


c) Thermogram – transmission method and profile plots of cells containing water



d) Thermogram method with microwave stimulation

Figure 3. Experimental results



a) IR thermogram (connection of upper surface) b) IR thermogram (connection of bottom surface)

Figure 4. PW-5 Rudder

3. LIGHT BALLISTIC PROTECTIONS

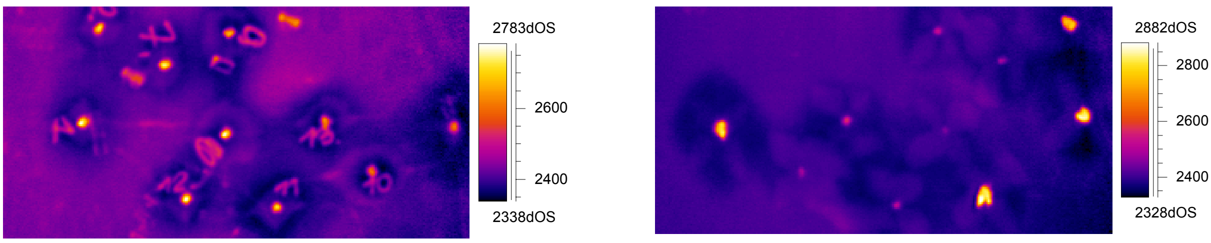
Nondestructive testing of light ballistic protections by infrared thermography is an interesting work carried out in MIAT. Research works made in MIAT were described in many papers [7-13]. The fiber reinforced polymer composites is the basic of light armour structures. The multi-layer structures are mainly made of the following materials:

- aramid fabrics as a fabrics with different constructions and the area-hyperbolic density ,
- prepregs the handicap moulding as aramid fabrics coated by the special resins,
- high performance poliethylene fibers as fabrics, modulus structures and composite plates,
- ceramic plates made on Al_2O_3, SiC, B_4C [7].

Defects of light ballistic protections can appear as result of impact. Other types of defects are the results of production process or a long-term use. Papers [8-13] include some results obtained at researching of different type of light ballistic protections when subjected to different kind of loads causing internal damage of composite.

Nondestructive testing by optical lock-in IR thermography was obtained on samples of light ballistic armours made from aramide and glass laminates in paper [13]. All samples before nondestructive testing were tested with ballistic limit V_{50} method. The resistance against fragments can be tested by measuring the ballistic limit V_{50} with standard fragments having mass 1,1 g. The test allows to compare different materials, first of all with regard to their surface density. This fragment is defined as standard fragment in Polish standards. Basic document of NATO is STANAG 2920 "Ballistic test method for personal armour" which contains requirements to carry out this test. Ballistic limit V_{50} is determined as an average velocity from 6 velocities of perpendicular hitting (3 lowest velocities with total penetration and 3 highest velocities with partial penetration).

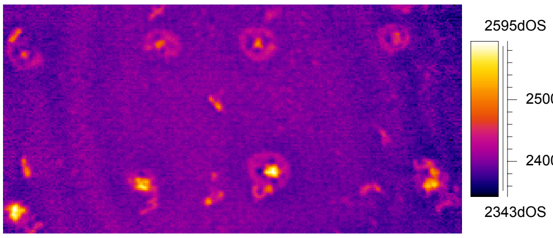
Examples of phase image of aramide laminate (6 layers) with subsurface delamination from side of ballistic impact and opposite side are present on Fig. 5. The zone of damage was defined as a diameter of the circle of internal damages of material in result of ballistic impact into the sample.



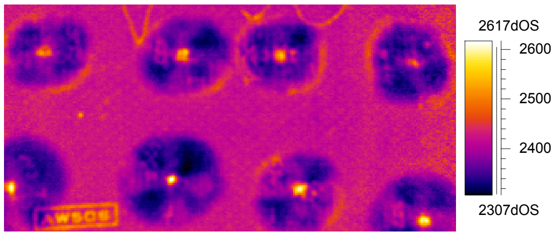
a) Phase image (0,04 Hz) of aramide laminate (impact side) b) Phase image (0,04 Hz) of aramide laminate (opposite side)

Figure 5. Testing results of sample of aramide laminate – 6 layers

Examples of phase images of glass laminate (15 layers) with subsurface delamination from side of ballistic impact and opposite side are presented on Fig. 6.



a) Phase image (0,04 Hz) of glass laminate (impact side)

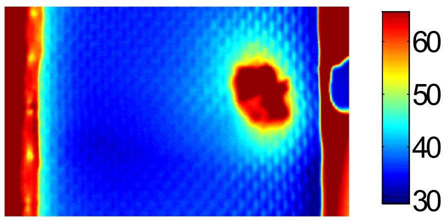


b) Phase image (0,04 Hz) of glass laminate (opposite side)

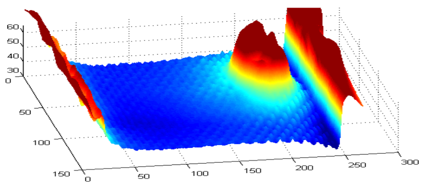
Figure 6. Testing results of sample of glass laminate – 15 layers

In the paper [9] introduced the diagnostic technique making possible the research of internal structures in composite materials using more often in construction of light armours that determine both the covers of vehicles and planes as and equipment for personal protection. Fig. 7 represents the results of research obtained at estimation of delamination area after execution of a ballistic protection testing on light armour (soft – being with packs of special fabrics). The test sample was made from multi-layered composite aramids. The thermography testing used a lock - in method. Fig. 7 a) represents a photography of aramides material to production of bullet-proof vests from the front side with ballistic impact. On Fig. 7 b) a phase image at f = 0.03 Hz and excitation power 900 W is represented. On this phase image an area of delamination around the ballistic impact (light blue color) is visible. Fig. 7 c) represents the phase of the image from Fig. 7 b) in form a of three-dimensional graph.

a) Photography of aramids material to production of bullet-proof vests.



b) Amplitude image (f = 0,03 Hz)



c) Amplitude image 3D

Figure 7. Sample with ballistic impacts

4. AMMUNITION

Pyrotechnic composite materials are widely used in military and civil applications as solid composite (heterogeneous) propellants and gas-generators in rocket motors. The nondestructive testing (NDT) methods are used to detect defects which can disturb normal working i.e. burning and gas generating of these products and decrease level of their performance characteristics. These defects are caused by different kinds of other material inserts (intrusions), voids, caverns (e.g. air bubbles), cracks and stratifications of different size, shape and density of material than main (matrix) material. Defects in composite pyrotechnic materials and products can become in production stage as well as in service time esp. during long-term storage. The diverse, changeable environmental conditions lasting in life cycles of pyrotechnic materials and products decide in considerably degree about their physicochemical characteristics such as thermal, mechanical parameters, stability, material compatibility and durability. In the paper [14] both computer simulations to define defects which could be detected using IR thermography method and selected experimental investigations are presented as well.

From statistics given in literature data it appears that basic reasons of rocket motors unstable burning often leading to failures, there are such defects like cracks, voids in propellant and de-bonding between propellant charge and its inhibiting layer. It was established that during operation of rocket motors these defects are able to cause rapid rise of propellant burning surface which induces violent increase of combustion products pressure in motor chamber sometimes leading to instabilities of rocket motor thrust course and/or to destroying even catastrophic rupture of rocket motor. To avoid above instabilities accompanying burning process of propellant charges caused by structural defects of propellant and ensure high level of probability / confidence of appropriate safety and operation reliability/suitability of rocket motor, there were evolved several non-destructive test (NDT) methods to detect, measure and assess defects in structure and integrity of propellant charges. These NDT inspection methods for solid rocket propellant charges are as follows: radiographic (X-ray) testing, computed tomography, neutron radiography, ultrasonic testing, infrared (IR) thermography, acoustic emission testing, optical holography and of course – visual inspection. Among NDT methods, radiography techniques have the widest usage, but they indicate some inconveniences/disadvantages because in dependence on X-ray absorption abilities of tested samples, these techniques require careful selection and adjustment of operation mode of X-ray source within the range of its radiation intensity. In several cases, X-ray techniques also need troublesome and time consuming measurements connected with determination of defects size and their positioning, in consequence bringing some difficulties in interpretation of X-ray images.

IR thermography can be divided into two kinds of testing, passive and active IR thermography testing. The passive method tests materials and structures which are naturally at different temperature than ambient while in the case of the active method, an external or internal stimulus is necessary to induce relevant thermal contrasts. Because pyrotechnic materials should be safe for the use at temperatures between - 40°C to + 55ºC esp. in military usage, the application of active IR thermpgraphy nondestructive testing methods is potentially attractive for their testing.

Fig.8 shows selected results on nondestructive testing sample of composite pyrotechnic material with defect. Fig. 8 a) presents radiography picture of sample with detected defect between inhibitor and pyrotechnic material. Fig.8 b) shows thermogram of this sample with a detected delamination. On thermogram is visible place, size and shape this delemination. This isn't visible on radiography picture.

A non-destructive testing method was used for newly developed composite nozzles of solid propellant rocket motors. Parts of these new nozzles are manufactured from the pyrolytic or electrode graphite and they replace nozzles made totally from the pyrolytic graphite. The reduction of manufacture costs decides about the nozzles design modification. In order to satisfy service dependability it is essential to provide nozzles with the possibly highest quality of workmanship. In order to do it the defective items with surface cracks must be identified and eliminated at the manufacture process. A possible way of achieving this is the application of the non-destructive testing by means of the infrared thermography method.

Papers [15-18] include some results obtained at researching composite nozzles of solid propellant rocket motors. Fig. 9 represents thermogram of composite nozzle with visible defects [17].

a) Radiogram b) Thermogram

Figure 8. Results on nondestructive testing sample of composite pyrotechnic material with defect

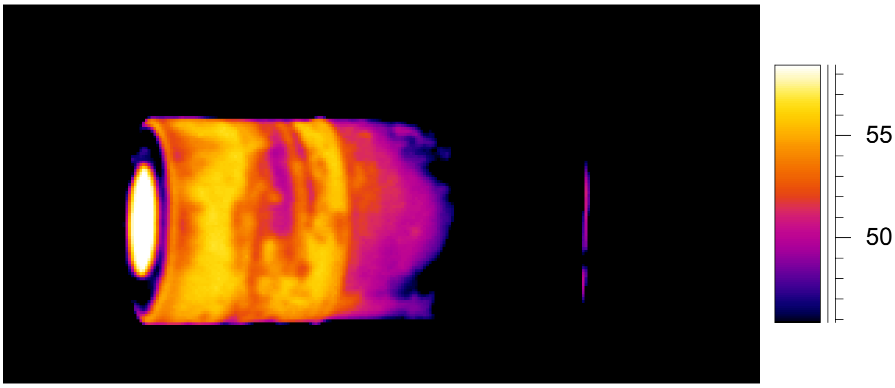


Figure 9. Thermogram of composite nozzle with defects

5. CONCLUSIONS

In the paper the main directions of works executed in MIAT were introduced. Regarding the fast development and use of more complicated composite materials in military applications the future works in MIAT over the exploitation of infrared thermography will be directed mostly on nondestructive testing of these materials.

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