IR THERMOGRAPHY METHODS ON NONDESTRUCTIVE TESTING OF BALLISTIC COVERS MADE OF MULTI-LAYER CARBON FIBER

Paweł Hłosta, Waldemar Świderski

Military Institute of Armament Technology
Wyszynskiego Street 7, 05-220 Zielonka, Poland
tel.:+48 22 7614549, +48 22 7614552, fax: +48 22 7614447
e-mail: phpph@wp.pl, waldemar.swiderski@wp.pl

Marek Szudrowicz

Military Institute of Armoured and Automotive Technology
Okuniewska Street 1, 05-070 Sulejówek, Poland
tel.: +48 22 6811025, fax: +48 22 6811073
e-mail: mszudrow@witpis.eu

Abstract

Presently a lot of designs of light armours are based mainly on the multilayer composite materials. Thanks to these materials it was possible to achieve highest levels of ballistic resistance of specific armour at limited weight. The weight (area density) and the performance have direct influence on the value of combat ability of equipment and soldiers. Carbon fibers are basic types of reinforcement used in composites. They have many technical applications including light ballistic covers where they are mostly used as multi-layer composite materials constituting a structure made of several interconnected layers or many layers of carbon fibers, or in combination with other materials.

Light ballistic covers have usually thickness of several to 10-20 mm and potential defects occurring in them have thermo-physical properties definitely different than materials they are made of so the non-destructive tests using thermography methods may be effective in detecting these defects.

The main methods of active thermographic tests are as follows [1, 2]:

- *Pulsed Thermography – PT,*
- *Step Heating Thermography – SHT,*
- *Lock-in Thermography – LT,*
- *Vibrothermography – VT.*

In the paper an application of Step Heating Thermography and Vibrothermography to detection of delaminating area of CFRP composites after mechanical impacts is presented.

Keywords: *IR thermography, light armour, CFRP composite, nondestructive testing*

1. Introduction

Protecting the crew of vehicles is one of main priorities at upgrading the Polish Armed Forces. More and more high levels of crew protection appear in technical requirements on new military equipment (mainly vehicles or their elements). These requirements may be met by using the newest solution of material engineering – light-weight ballistic covers.

More and more often composite materials are used for fabrication of light-weight ballistic covers. An interest in these covers comes from threats for troops participating in stabilization missions. Usually these troops use motor vehicles exposed to small-arms fire and mine explosions. Therefore it is necessary to provide an effective protection for these vehicles that assures an adequate safety level for their crews [1]. Composite materials are characterized by excellent mechanical and strength-related properties, combined with a low specific weight. This combination of features actually occurs only in composites and this is the reason why their application in design of light ballistic covers, where these features are of a paramount importance, has been recently growing rapidly. One of the basic groups of reinforcement materials in composites are carbon fibres discovered back in 19th century [3]. They have many technical applications including light ballistic covers where they are most often used as multi-layer composite materials constituting a structure made of several interconnected layers or many layers of carbon fibres, or in combination with other materials.

2. Investigation problem

The composite components and technologies for their integration in light armours are chosen to provide required functional characteristics. Quality requirements during their production and long-life service have generated the demand for efficient methods and diagnostic techniques. Diagnostic procedures have to provide:

- nondestructive testing,
- high detectability of defects and damages,
- high speed of inspection,
- mobilities of inspection stand.

The main reason of defects in structures of composite materials used in light armours is variability of working loads on constructions during the service life. These defects are mostly complicated because of breaks in reinforced fibres, cracks of binder and loss of adhesiveness between fibers and binder. Classical diagnostic methods (X-ray, ultrasounds) are not very useful at testing composite constructions because defects of composite materials are usually more complicated than in metals. This situation caused the search of new diagnostic methods adapted to specificity of composite materials. A method that has proved to be useful at testing of composite materials is IR thermography [4-6] thanks of its not invasiveness, high effectivity and universal character.

Nondesructive testing carried out with IR thermography method provides the results in the form of quickly recorded images. In the case of testing of light composite armours the IR thermography process is limited to the production of temperature distribution maps (thermograms) on the surface of material.

Usually the IR thermography testing can be made with two methods [7]:

- passive – when realization of testing does not require any special thermal extortion,
- active – when realization of testing requires a special thermal extortion because it is not available by the natural way.

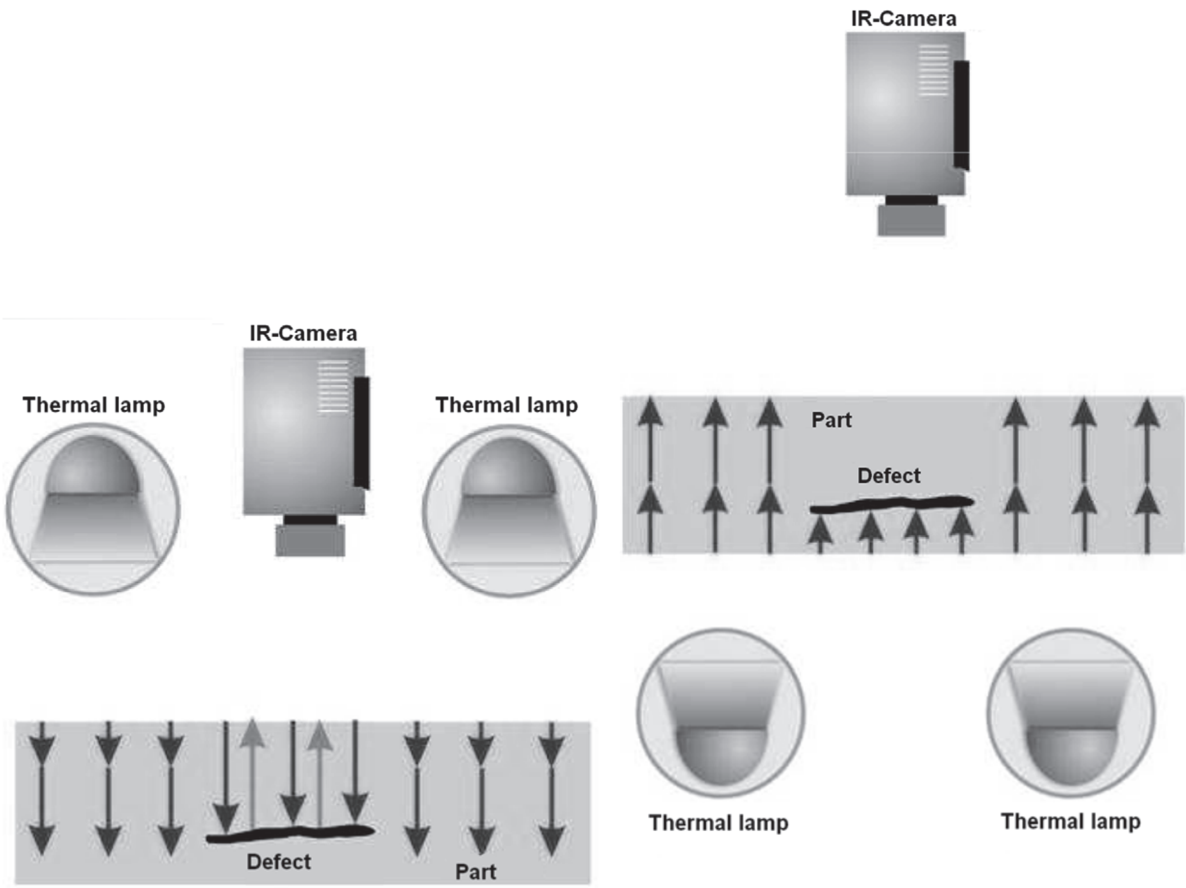
The testing of composite light armours with IR thermography method demands the active method to be used. Causing the heat flow for needs of thermography diagnostics can be achieved by the treatment of an external surface (lighting, direct contact with a jet of liquid or solid) or an internal structure (through mechanical excitation e.g. vibrations, change of pressure, eddy currents flow, inductive heating or microwave etc.). The selection of a proper method for this treatment is a multi-parameter element of optimization and it has strong impact on effectiveness of troubleshooting process.

3. Used methods

The main methods of active thermographic tests are as follows [1, 2]:

- Pulsed Thermography – PT,
- Step Heating Thermography – SHT,
- Lock-in Thermography – LT,
- Vibrothermography – VT.

One of main methods of active thermography – Step Heating Pulsed Thermography (SHT) was used to check the effectiveness of defect detection in multi-layer carbon composites. Pulsed thermography is currently one of the most popular methods used in non-destructive tests for relatively thick composite materials of low conductivity. Tests of this kind use a lamp, laser, etc. to generate a thermal exciting pulse (or series of pulses) that lasts from several seconds to tens seconds. Step heating thermography can be used in both reflective and transmission method (Fig. 1). A sequence of images (thermograms) is recorded at constant intervals between the images. Having switched the radiation source off the object tested is cooled down to the ambient temperature. In the cooling phase a temperature distribution across the surface of the object is determined and analysed. Depending on thermal properties of the material tested and defects hidden under its surface, areas of a higher or lower temperature will indicate zones where material defects may occur. Often special thermogram processing techniques need to be used to identify the defect areas.Using the most popular optical heating (e.g. a heating lamp) is also connected with drawbacks of this kind of warming including: 1) non-uniform heating; 2) low temperature contrast resulting from the fact that both defect areas and these not containing any defects are heated up; 3) difficulties with detection of deeper located defects that require larger thermal energy what may result in damage of the sample through overheating. In order to reduce effects of these shortcomings a thermal stimulation by means of vibrothermography with ultrasonic thermal excitation of material began to be used [8, 9]. Ultrasounds cause first of all a temperature increase in the fault area that significantly increases the temperature contrast value. In order to compare a possibility of increasing the probability of defect detection in multi-layer carbon composites there were tests conducted using the pulsed thermography method by means of both a heating lamp and an ultrasonic source. Fig. 2 presents the set-up used for thermographic tests with ultrasonic thermal stimulation.



a) b)

Fig. 1. Set-up of a stand for step heating thermography a) reflection mode, b) transmission mode

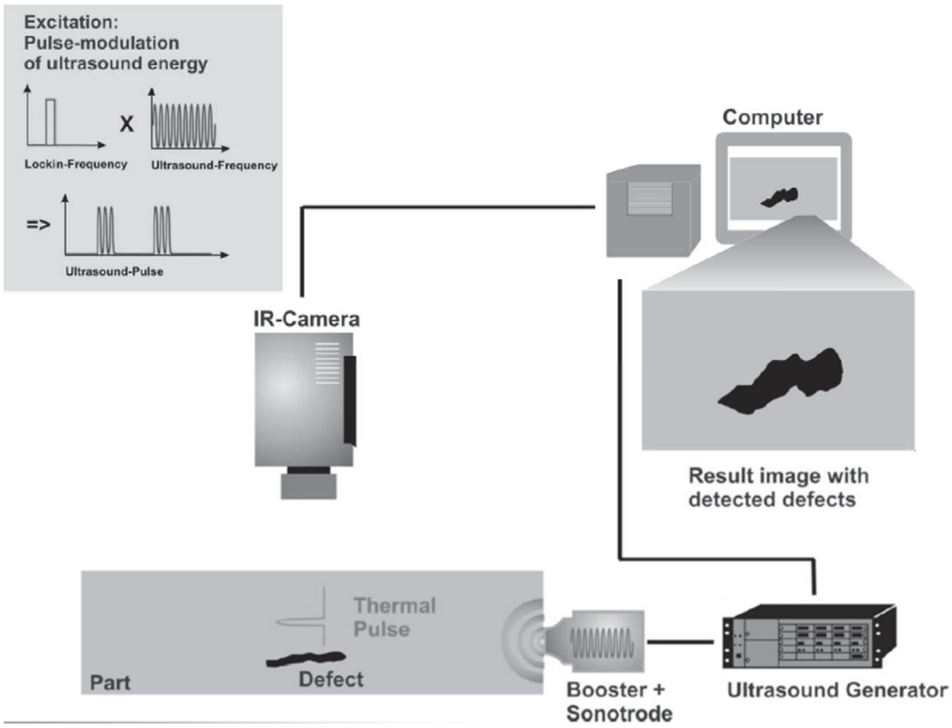
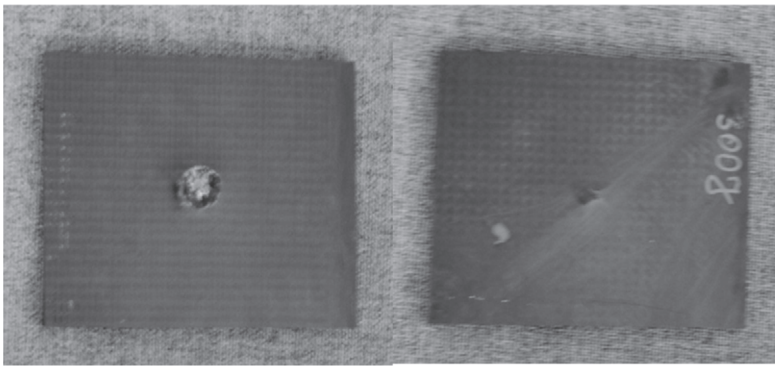
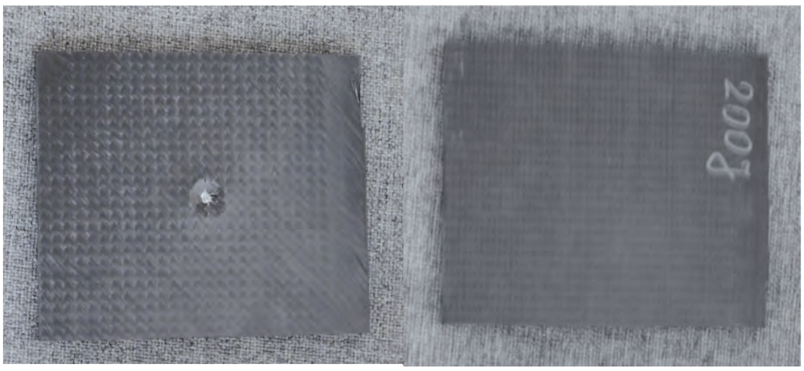


Fig. 2. Set-up of a stand for vibrothermography with ultrasonic thermal excitation



a) b)

Fig. 3. The sample after impact force about 300 J: a) impact side, b) opposite side



a) b)

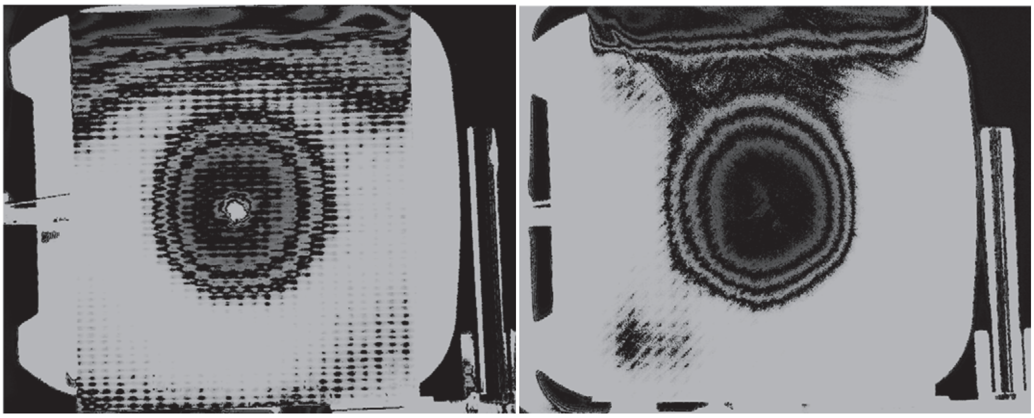
Fig. 4. The sample after impact force about 200 J: a) impact side, b) opposite side

4. Experimental tests

Three samples of multi-layer (14 layers) carbon-fiber composite were examined in the experimental tests. These samples were after mechanical impacts of different forces: 100 J, 200 J and 300 J. Fig. 3 presents the sample after impact force of 300 J. All samples were used for comparison tests by step heating thermography method (transmition mode) with optical thermal stimulation and vibrothermography with ultrasonic thermal stimulation. A lamp was used as the source of the optical pulse of 2 kW output power and duration of 10 s. An ultrasonic pulse of frequency of 30 kHz and 100 W output power was generated by the ultrasonic generator. The FLIR SC 7600 camera (InSb, 640x512 pixels, 17 mK) was used for recording the changes of temperature field on the sample surface by recording sequences of thermograms (1600 images in a sequence) at 5 Hz frequency.

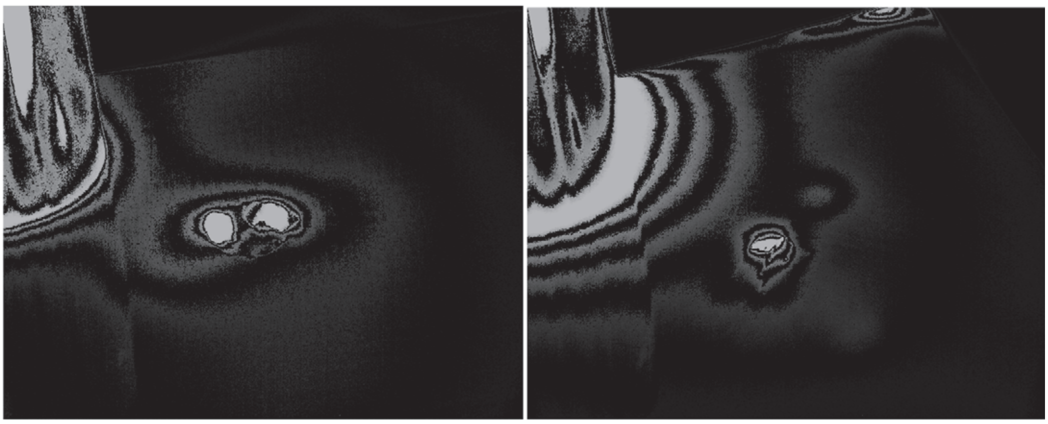
5. Test results

Figure 5 shows results of internal damage of the multi-layer carbon-fiber composite structure on both the impact side (Fig. 5a) and the opposite side (Fig. 5b)after hitting with impact force about 300J (Fig. 3) obtained by step heating thermography method. Damages have shape approximate to circles of different diameters and they are visible in individual layers of composite.



a) b)

Fig. 5. Thermograms of the sample after impact force about 300 J – step heating thermography method: a) impact side, b) opposite side

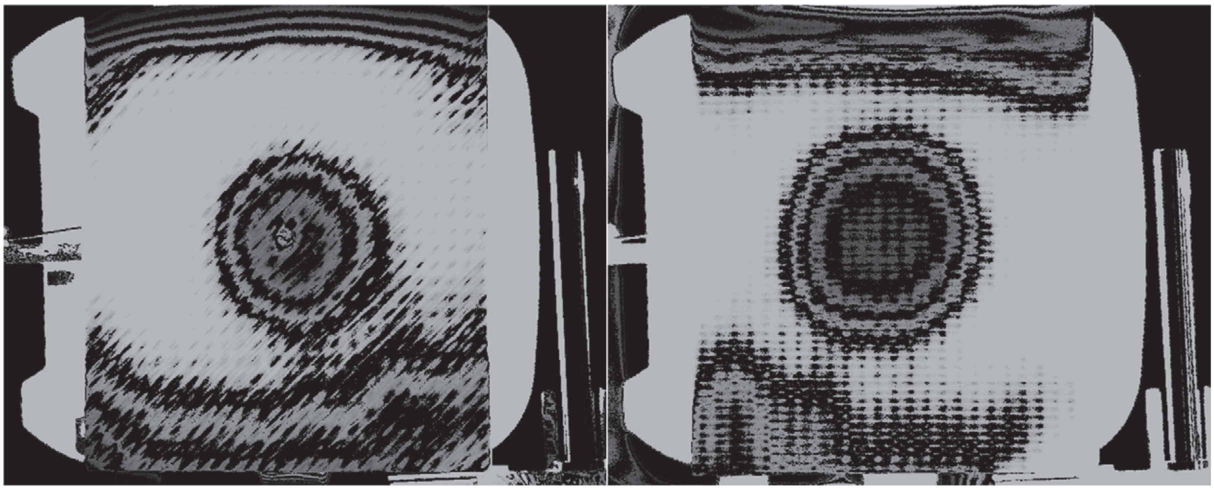


a) b)

Fig. 6. Thermograms of the sample after impact force about 300 J – vibrothermography method: a) impact side, b) opposite side

Figure 6 presents thermograms of the sample (Fig. 3) too but obtained by vibrothermography method. The essential differences are visible in comparison of results of both methods. The vibrothermography method shows place where the internal damages of material are the largest.

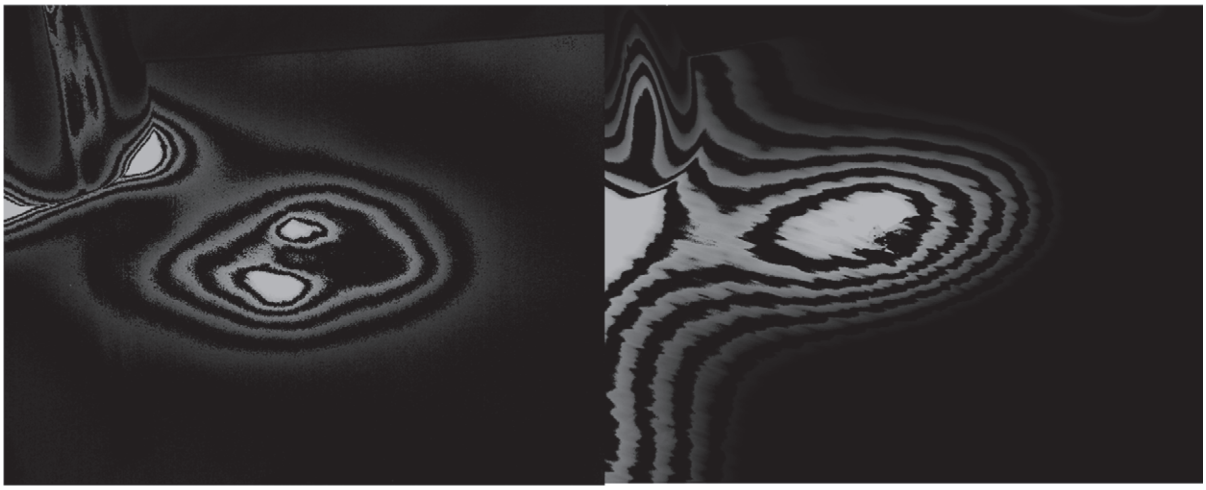
Figure 7 presents thermograms of sample (Fig. 4) after impact force about 200 J obtained by step heating thermography method. These results are very similar to results of sample with impact of 300J. Smaller quantity of damaged layers is visible because the energy of impact was smaller.



a) b)

Fig. 7. Thermograms of the sample hit with impact force of 200 J – step heating thermography method: a) impact side, b) opposite side

Figure 8 shows thermograms of the sample hit with the impact force of 200 J obtained by vibrothermography method. The places of the largest damage of material are visible on these thermograms both with the areas of damage at different depths.



a) b)

Fig. 8. Thermograms of the sample after impact force about 200 J – vibrothermography method: a) impact side, b) opposite side

6. Conclusions

The comparison of step heating thermography (transmition mode) with optical stimulation and vibrothermography with ultrasonic stimulation method has shown that:

– the tests of all samples show that currently there are technical possibilities of detecting defects in all layers of carbon-fibre multi-layer composites with the thickness above 10 mm by means of IR thermography methods,
– we obtained better results by step heating thermography method but cause of worse results of vibrothermography method may be explained by the use of only one frequency of ultrasonic

stimulation (equipment limitations),

– in spite of worse results of vibrothermography method it shows some details of defects, which aren't detected by the step heating thermography method, so these results are complementary in some degree.

In further experiments we would like to focus on the following objectives:

– use of vibrothermography method with different frequencies of ultrasonic stimulation,
– use of eddy currents for thermal stimulation of tested multi-layer carbon composite material.

References

[1] Swiderski, W., *Nondestructive Testing of Composite Materials by IR Thermography Methods*, Monograph, WITU, Zielonka 2010, (in Polish).

[2] Maldague, X. P. V., *Theory and Practice of Infrared Technology for Nondestructive Testing*, John Wiley&Sons, p. 78, New York 2001.

[3] Dobrzański, L. A., *Non - metal Engineering Materials,* Wydawnictwo Politechniki Śląskiej, Gliwice 2008, (in Polish).

[4] Henneke, E. G., and Reifsnider, K. L., *Thermography-applications to the Manufacture and Nondestructive Characterization of Composite,* SPIE, Vol. 0371, pp. 98-104, 1982.

[5] Jones, T. S., Lindgren, E. A., and Pergantis, C. G., *Infrared Inspection of Advanced Army Composites,* SPIE Vol. 2473, Thermosense XVII, pp. 214-218, 1995.

[6] Swiderski, W., *Lock-in Thermography to Rapid Evaluation of Destruction Area in Composite Materials Used in Military Applications*, SPIE, Vol. 5132, pp. 506-517, 2003.

[7] Maldague, X. P. V., *Nondestructive Evaluation of Materials by Infrared Thermography*, Springer-Verlag, 1993.

[8] Vavilov, V.P., *IR Thermography and Non-destructive Evaluation,* «Спектр», Moskwa, p. 544, 2009 (in Russian).

[9] Favro, L. D., Han, X., Ouyang, Z., et al., *IR Imaging of Cracks Excited by an Ultrasonic Pulse*, Proc. SPIE Thermosense-XXII, Vol. 4020, pp. 182-185, 2000.