EXPERIMENTAL INVESTIGATIONS OF DEFECT SIZING IN COMPOSITE MATERIALS BY IR THERMOGRAPHY METHODS

W. Swiderski[a*], M. Szudrowicz

[a]*Military Institute of Armament Technology, 05-220 Zielonka, Wyszynskiego 7 Str., Poland*
[b]*Military Institute of Armoured and Automotive Technology, 05-070 Sulejwek, Okuniewska 1 Str., Poland*
**waldemar.swiderski@wp.pl*

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Abstract
The infrared thermography non-destructive testing methods prove to meet the expectations well in composite constructions. The main reason of defects in the structures of composite materials is the variability of working charges in constructions during their lifetime. Visible defects are usually complicated because of the occurrence of continuity gaps of reinforced fibres, binder cracks and loss of fibres adhesiveness from binders. The diagnostics that exploits a method of infrared thermography is applied more often in recent time. An infrared diagnostic technique that makes possible to carry out the research works and tests of internal structures in composite materials used more frequently in construction is presented in the paper. Comparison of detection defect sizing in composite sample (CFRP and GFPR) after mechanical impact by IR thermography methods with -stimulation by means of the optical and ultrasonic as well as lock-in thermography method will be presented.

1. Introduction

Composite materials are created by a combination of two or more types of material with different physical or chemical characteristics. Usually composite materials are made artificially to obtain proprieties, which couldn't be got separately by any of their components.
The wide group of composite materials uses reinforced fibres. These materials are usually rigid but also brittle and by mixing them with a soft and ductile resin a composition may be obtained, that provides static and fatigue strength and the rigidity as well. Composite materials of this group can show high strength proprieties both in room and high temperatures too. There are many different types of reinforcing fibres used in composite materials. Straw was used as fibre to reinforce bricks made from clay and river sludge in antique Egypt. These materials were the first composite materials made by man in the world [1].
There are different types of fibres applied in composite materials both with polymer and ceramic wraps at present. Multi - layer composite materials using reinforced aramid, carbon and glass fibres are often used in construction of light armors for protecting vehicles. It was in the thirties of 20th century when glass fibres were applied to reinforcement of composite materials. They can be applied individually or as roving to made fabrics and mats to reinforce composites. Carbon fibres discovered in the 19th century are the basic reinforcement material and have been used in composites to produce many industrial articles since the fifties of the 20th century. Aramid was invented in 1965 by Stephanie Kwolek (DuPont). Aramid fibers are

a class of heat-resistant and strong synthetic fibers. They are used in aerospace and military applications [2]. Epoxy and phenol-formaldehyde resins are the most often applied ones for joining multi-layer composite materials in military applications.
Composite materials with reinforced fibres are especially interesting for military applications through their good strength properties, corrosion resistance and low specific weight. Any damage of these materials usually has a more complicated and different 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 [3]. The main reason of defects in the structures of composite materials is the variability of working charges in constructions during their lifetime.

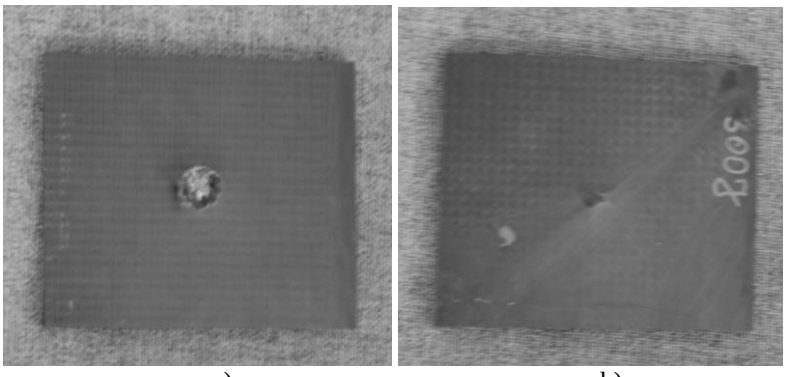
2. Experimental materials and methods

2.1. Materials

Tests have been performed on samples of 15-ply carbon fiber reinforced plastic (CFRP) (thickness 11.6 mm) and samples of 15-ply glass fiber reinforced plastic (GFRP) (thickness 11.6 mm) against impact resistance at the Military Institute of Armoured and Automotive Technology in Poland. Table 1 presents fatigue strength parameters of glass and carbon fibres used in composite materials. The resistance of composites against impact can be evaluated by subjecting six samples (three CFRP and three GFRP) to mechanical actions of different forces (100J, 200J and 300J). Examples of both surfaces of the samples are shown in Fig. 1 (CFRP) (note that «F» specifies the front (impacted) sample surface, while «R» is related to the rear surface) and Fig.2 (GFRP).

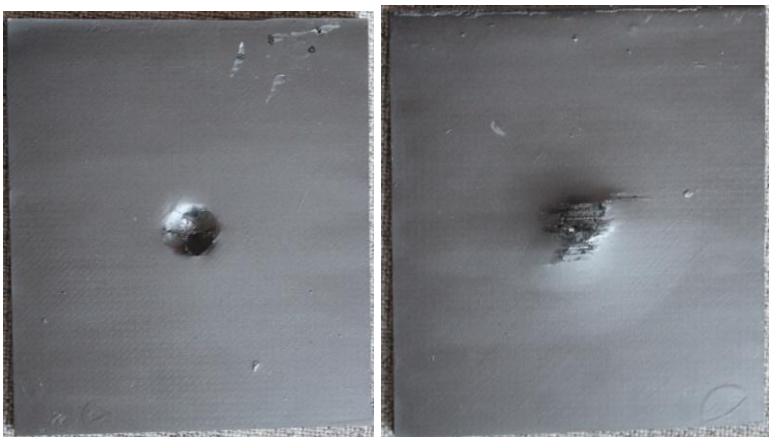
Parameter	**Glass fiber**	**Carbon fiber**
Density [kg/m^3]	2150 ÷ 2540	1740 ÷ 1820
Young's modulus [GPa]	69 ÷ 91	228 ÷ 294
Tensile strength [MPa]	3100 ÷ 4400	3100 ÷ 3600
Proper modulus [km x 10^3]	3.1 ÷ 3.7	13.4 ÷ 16.5
Proper strength [km]	124 ÷ 181	211 ÷ 398
Percentage elongation [%]	4.8 ÷ 5.7	1.5 ÷ 2.4
Maximum working temperature [℃]	500 ÷ 1050	500

Table 1. Parameters of fibers [3]



a) b)

Figure 1. The sample of CFRP after mechanical impact force of 300J: a) front (F) surface - impact side, b) rear (R) surface



a) b)

Figure 2. The sample of GFRP after mechanical impact force of 300J: a) front (F) surface - impact side, b) rear (R) surface

2.1. Methods

Typical defects of multi-layer composite material are delamination, a lack of adhesives, condensations and crumpling. There are similar defects after mechanical impact. IR thermograpic NDT is considered as an effective technique to detect such defects.
Pure optical and ultrasonic ways of heating were applied at testing composite samples (CFRP and GFRP) additionally with Lock-in thermography method.
One of main methods of optical 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 to generate a thermal exciting pulse (or series of pulses) that lasts from several seconds to ten seconds. Step heating thermography can be used in both reflective and transmission method. A sequence of images (thermograms) is recorded at constant intervals between the images. Having switched the radiation source off the tested object 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 indicate zones where material defects may occur [4]. In our tests a lamp was used as the source of the optical pulse with 2 kW output power and duration of 10 s and FLIR SC 7600 camera for recording the changes of temperature field on the sample surface.
Optically activated thermograhy reveals not only hidden defects but also other thermal features within the thermal depth range. Heat can also be generated directly in damaged areas when they are exposed to powerful excitation of ultrasound and its energy is converted into heat mostly in areas of stress concentration and defects like cracks or delamination [5]. These sources of heat can be detected by an infrared camera even in the presence of complicated intact features. Ultrasound activated thermography is a defect selective “dark field” NDT-technique as only defects produce a signal [6, 7].
The phenomenon of mechanical hysteresis seems to be vanishing in the range of typically used ultrasonic frequencies and electrical powers (from 20 to 40 kHz and up to a few kW respectively) [8, 9], therefore, a sound composite remains ‘cold’ during stimulation, while noticeable temperature signals appear in defective areas due to internal friction. The experiments at MIAT have been fulfilled by means of a FLIR SC 7600 IR imager (image format 320×256, acquisition frequency 5 Hz, up to 1600 images in a sequence). Continuous ultrasonic stimulation was performed with a piezoelectric unit at the frequency of 30 kHz with

the power from 80 to 130 W (maximum allowed power up to 2 kW). Fig. 3 presents the set-up used for thermographic tests with ultrasonic thermal stimulation.
In Lock - in method, which is used in this experiment, thermal wave has sinusoidal shape. This wave propagates both across the surface and inside of an object. When thermal wave comes to areas possessing different propagation parameters, it will be reflected. Reflected wave reaching the surface of testing object will interfere with the surface wave and because of its sinusoidal shape it has a different phase with relation to the surface wave. This makes imaging areas appear on the surface of object and they reflect different properties under the sample surface. These interferential images illustrate the existence of subsurface defects.
The set-up for experimental testing with Lock - in method is presented in Fig.4. The thermal wave is generated by a heat source, which is the lamp of about 1 kW power. The heat source is calibrated by the Lock - in Module, which provides sinusoidal form of thermal wave at specific frequency [10, 11].

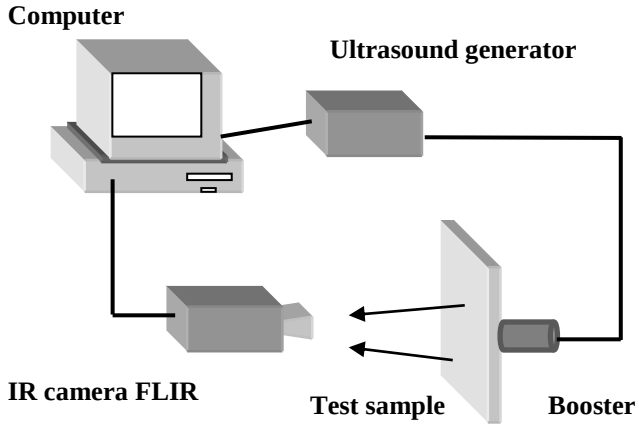


Figure 3. Set-up of vibrothermography method with ultrasonic thermal excitation

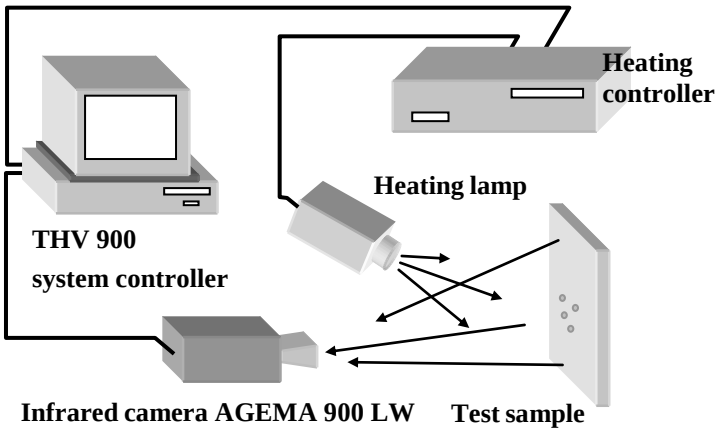


Figure 4. Lock-in thermography - experimental set-up

In order to get interference images the THV 900 System Controller collects the series of images and compares their temperature and performs the calculations of amplitude and phase angle of imaging thermal wave in every point of the image. Amplitude and phase images are not disturbed by secondary radiation from the surface of testing object. The phase image is undisturbed by differences in emissivity of the surface and non-uniform distribution of heat emitted by the source.

The system Lock - in divides each cycle of the thermal wave on four equal parts and collects an equal number of images in each part. Images from each part are averaged to produce four images with averaged signal values of thermal camera.
The phase and amplitude is then calculated for each pixel of the image according to following equations [11, 12]:

$$T(x,t) = T_0 e^{-\sqrt{\frac{\omega \cdot \rho \cdot c_x}{2\lambda}}} \cdot \cos\left(\omega \cdot t + \sqrt{\frac{\omega \cdot \rho \cdot c_x}{2\lambda}}\right) \quad (1)$$

where:

- μ - penetration depth;
- λ - thermal conductivity;
- $\omega = 2\Pi$ - wave frequency;
- ρ - density;
- c – heat capacity;
- x – x axis coordinate;
- α - thermal diffusivity.

$$\alpha = \frac{\lambda}{\rho \cdot c} \quad (2)$$

The amplitude of thermal wave decreases to 37% (1/e) of the surface value at the following depth [12]:

$$\mu = \sqrt{\frac{2\lambda}{\omega \cdot \rho \cdot c}} = \sqrt{\frac{2\alpha}{\omega}} \quad (3)$$

The depth of penetration of attenuated thermal wave into the given medium does not depend only on thermal parameters of material (thermal conductivity, heat capacity and density) but also on the cycle time of this wave. By increasing the cycle time of wave it is possible to get deeper into testing object. Then it is possible to analyze each layer of a testing object and in such way to deal with so called tomography in the infrared radiation.

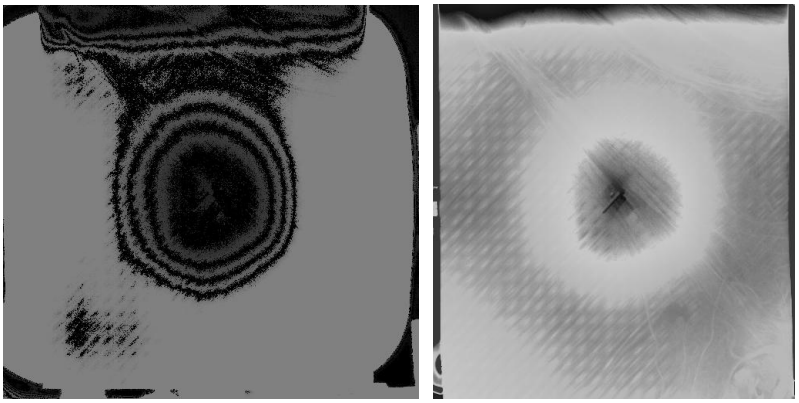
3. Results and discussion

Thermal inspection provides possibilities for definition not only lateral dimensions but depths and thickness of internal defects (damages) existing under the surface of tested object.
It is known with literature [13] that:

1. Transversal dimensions of internal defects can be directly evaluated on the basis of their superficial temperature “footprints” or a simple analysis of superficial temperature profiles with accuracy between 5 to 10%.
2. Depth of location of defects can be evaluated with accuracy from 20 to 30%.
3. Thickness of defects or their thermal resistance can be evaluated with accuracy from 30 to 60%.

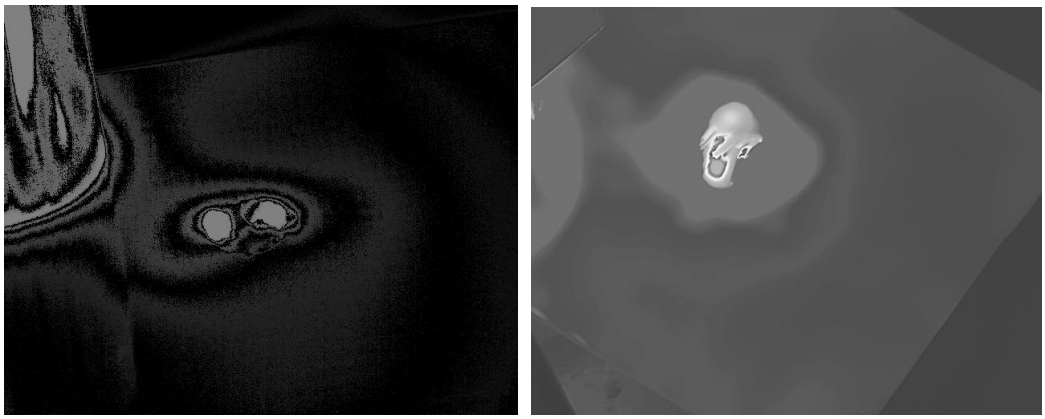
It results from this that contrary to the depth of location and thicknesses, lateral dimensions of damages can be evaluated on basis of simple visual evaluation of temperature “footprints”, which damages created on surface of tested object. The qualification of depth and thickness of

damages requires solution of inverse problems of thermal investigations through inversion of numerical results of direct solution of problem and their approximation by inversion formulas. Direct solutions can be both analytical and numerical. During destructive tests the structure of samples of CFRP and GFRP composites is destructed in all thickness in places of mechanical impacts. Therefore we have limited our work to evaluation lateral dimensions of internal damages and the comparison of results received by different methods applied in these tests.
Figures 5-7 show exemplars of thermograms, received for the multi-layer CFRP and GFRP composite materials after applying mechanical impacts, obtained by step heating, vibrothermography and lock-in thermography methods.



a) b)

Figure 5. Thermograms of samples after using impact force of 300 J – step heating thermography method (transmition mode): a) CFRP rear (R) surface b) GFRP rear (R) surface



a) b)

Figure 6. Thermograms of samples after using impact force of 300 J – vibrothermography method: a) CFRP - front (F) surface b) GFRP- front (F) surface

Figure 8 presents comparison of sizes of damages evaluated as radius of area of internal damages detected by used thermography methods. These results are mean values of following methods:

- direct measurement of visual thermal "traces" of damages on thermograms,
- Full Width Half Maximum – described in paper [14], in which qualification of geometrical dimensions of defect (damage) is made on the basis of points corresponding to the half of maximum temperature drop value of signal $\Delta T_m / 2$,

- procedure described in paper [15], in which was show, that extremum of derivatives from $T(x, y)$ in relation to any superficial co-ordinate represents mapping borders of internal damages on the tested surface.

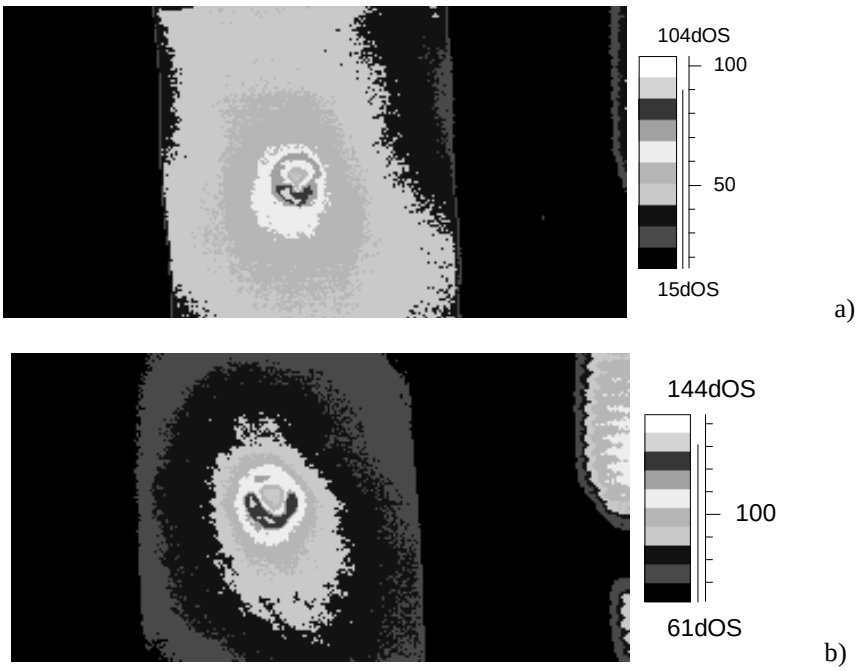


Figure 7. Phase images at 0.5 Hz of samples after using impact force of 300 J – lock-in thermography method: a) CFRP - front (F) surface b) GFRP- front (F) surface

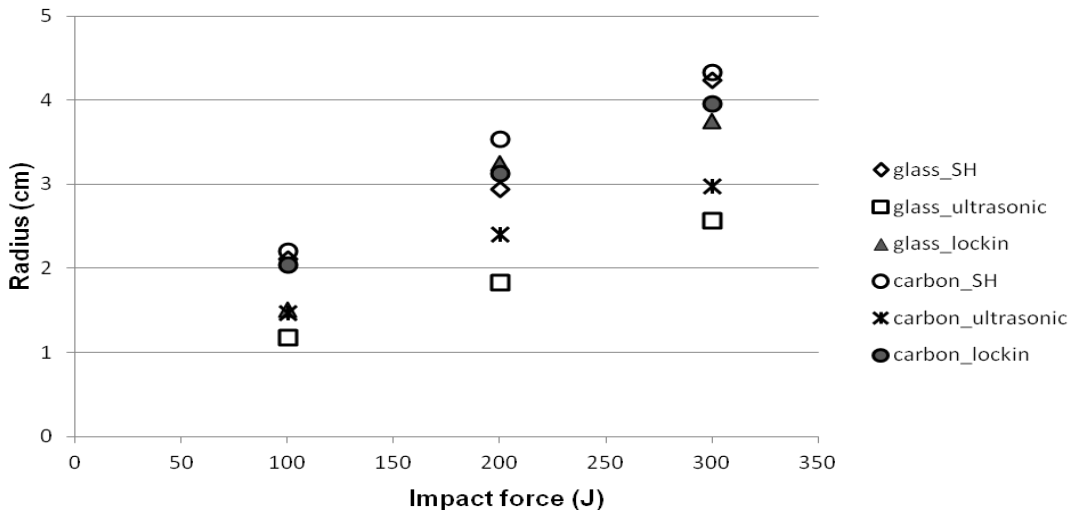


Figure 8. Comparison size of damages detected by different thermography methods.

4. Conclusions

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

- the tests of all samples shown that currently there are technical possibilities of detecting defects by means of IR thermography methods in all layers of carbon-fibre multi-layer composites with thickness above 10 mm,
- we obtained better results by step heating thermography method but cause of worse results by vibrothermography method may be that it was applied only one frequency of ultrasonic stimulation (equipment limitations),
- lock-in thermography gives similar results to step heating thermography method,
- in spite of worse results vibrothermography method shown details of defects, which were not detected by step heating thermography method and lock-in thermography, so these results completed mutually.

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

- use of vibrothermography method with different frequencies of ultrasonic,
- focus on increasing possibilities for defining destruction zones in individual layers of material by using special techniques of image processing.

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