Przemysław D. PASTUSZAK[1*], Małgorzata CHWAŁ[1], Aleksander MUC[1], Jarosław BIENIAŚ[2]

[1] Institute of Machine Design, Cracow University of Technology, Poland

[2] Department of Materials Engineering, Lublin University of Technology, Poland

* Corresponding author: ppastuszak@pk.edu.pl

Identyfikacja defektów w cylindrycznych laminatach szklanych przy wykorzystaniu aktywnej termografii

Streszczenie. *W prezentowanej pracy przedstawiono identyfikację podpowierzchniowych defektów w cylindrycznych laminatach szklanych z wykorzystaniem termografii w podczerwieni. Analizie poddano jednokierunkowe laminaty o dwóch konfiguracjach: 0° (S0) oraz 90° (S90), w których pomiędzy warstwy laminatu wprowadzono sztuczny podpowierzchniowy defekt w formie teflonowej folii. Analizę termograficzną prowadzono bazując na technice impulsowej, a rezultaty zaprezentowano w formie termogramów i profili temperaturowych. Wyniki analizy potwierdziły przydatność impulsowej aktywnej termografii w badaniu cylindrycznych struktur kompozytowych. Dodatkowo podkreślono problem jednorodnego nagrzewania powierzchni zakrzywionych.*

DEFECT IDENTIFICATION IN GFRP CYLINDRICAL PANELS BY ACTIVE THERMOGRAPHY

Summary. *The presented paper is dedicated to infrared thermographic identification of subsurface defects in cylindrical panels made of glass lamina. The analyzed samples were made as unidirectional lamina in the case of two base configurations: 0° (S0) and 90° (S90) in which the artificial subsurface defect was in the form of Teflon foil introduced between the layers in the structure. The thermography study based on the pulse technique was conducted and the results were presented in the form of thermograms and temperature profiles. The effects of the analysis confirmed the usefulness of the pulsed active thermography method related to cylindrical composite structures. Additionally, the problem with the uniform heating of the curved surfaces was depicted.*

1. INTRODUCTION

Composite materials are extensively used in many areas of industry, but they are particularly significant in the aeronautics, where light, strong and reliable structures are required to build the components of the aircrafts. Significant advantage of composites, compared to isotropic materials, is the opportunity to obtain different directional characteristics. This situation creates new possibilities for modern structure designs. Nevertheless, high mechanical properties of composites, mainly specific strength and specific stiffness can be effectively reduced by various forms of failure, particularly fiber breakage, fiber debonding, matrix cracking and delaminations [1-3].

Delaminations combined with the other forms of composite damage such as matrix or fiber breakages which might interact and develop, significantly decreasing the mechanical properties of the structural components and could finally lead to catastrophic failures [4].

Based on the aforementioned points, the importance of technical diagnostics of composite materials in the case of quality control is significant. The technical diagnostics of composite materials contains: detection, localization and geometrical characterization, and defect type description. The ability to evaluate defects in

Table 1. Characteristics of NDT methods [5,6]

Feature \ Method	Ultra-sound	Acoustic emission	Thermo-graphy	Eddy current	Tomo-graphy	Penetrant testing	Visual testing
Suitable with metallic sample	+	+	+	+	–	+	+
Suitable with composite sample	+	+	+	–	+	+	+
Direct test on sample	–	+	+	+	–	+	+
Sample size	–	+	+	+	-	+	+
Complex sample geometry	+	+	+	–	+	–	–
Testing within the structure	+	+	+	–	+	–	–
Environmental respect	+	+	+	+	–	–	+
Method implementation	–	+	+	+	–	+	+
Possible automation	+	–	+	–	+	–	+
Efficiency	–	+	+	+	–	+	+

(+) agreement with the specified feature; (–) disagreement with the specified feature

the structure has a crucial influence on the assessment of the reliability of the objects, which is directly linked to health risks or human life, e.g. aerospace industry.

Non-destructive techniques (NDT) play a vital role in the quality control of materials. These methods can be applied at different stages of the manufacturing process as well as beyond the fabrication where the quality of the structure is analyzed. Furthermore, NDT can be done in current and periodic inspections of the equipment while in use – health monitoring. Nowadays we have a lot of non-destructive methods (Table 1). However, there is strong attention being paid to the development of advanced measurement techniques that allow non-contact and fast examination of structures [5,6]. The infrared thermal imaging techniques suit well to this group of non-destructive methods to identify and quantify unseen defects in a vast range of composite materials.

The most important impulse for the development of the infrared (IR) thermographyis is their potential to reveal the subsurface features of structures. Moreover, there is an increasing interest in illustrating the spatial dissimilarity of thermal properties in heterogeneous materials such as composites. Structural defects, e.g. cracks and delaminations have significant influence on the thermal transfer which can be applied in order to form an image of the imperfection. This is the motivation to use thermal imaging as the non-destructive technique. However, the detect ability of the subsurface defects is crucially limited by the depth at which the discontinuities occur [7]. The effectiveness of the IR thermography in the polymeric composite materials' analysis is connected mainly with the low thermal conductivity and the high emission for such materials.

The main goal of the presented paper was focused on the application of the pulse thermography in order to identify the subsurface defects artificially introduced to the multilayered cylindrical glass/epoxy panels. The choice of cylindrical glass/epoxy panels was determined throughout the wide range of engineering application of such structures. In order to create artificial delamination in the investigated specimens a Teflon foil was introduced between the layers of the tested samples. The results are presented for eight-ply samples with two fiber orientations: 0° (S0) and 90° (S90).

2. INFRARED THERMOGRAPHY

The fundamental principles of using IR thermography to solve various problems are well documented [9,10,11,12,13] but some crucial facts about it should be mentioned in this work in order to highlight the ongoing research.

In Layman's terms, thermography is a complex process that allows us to imagine part of the infrared spectrum, thus obtaining useful information given in the form of thermal images that can be subjected to further analyses. Infrared radiation is a result of electron excitation of atoms and molecules, their rotations and oscillations. It is transferred through steam, liquids, gases, and also solids. Due to the different properties of infrared detector capabilities and optical materials, the spectrum of infrared radiation wavelength was conventionally divided into:

the near infrared – 0.78 to 1.5 [μm],
the middle infrared – 1.5 to 20 [μm],
the far infrared – 20 to 1000 [μm] [9].

The infrared thermography can also be divided into passive and active procedures. To detect undesired deviations, passive infrared thermography (PIRT) employs the current temperature of the examined object during normal operation or immediately after its end, when the temperature contrast on the surface may indicate possible damage. Defects radiate or absorb the heat resulted from the mechanical or thermal loads, occurred during the working of the examined object, so they can be identified by passive methods. Advantages of this configuration are direct on-site interpretation of the results without additional equipment. On the other hand, when the object is stimulated through an external energy source during the measurement, active infrared thermography (AIRT) is used. In order to obtain the thermal contrast between defective and homogenous regions, the dynamic temperature field (heating or cooling) is generated by an external energy source (e.g. halogen lamp). Most of the excitation ways can be classified as optical, mechanical or inductive. Taking into account the nature of excitation (pulse or sinusoidal) and data processing, the AIRT can be distinguished into pulse (PT), lock-in (LT), pulse phase (PPT) and vibrothermography (VT) [9,10].

Other classification of AIRT methods according to the physical characteristics of the excitation is given below:

a) type of thermal stimulation,
b) form and size of the induced area,
c) arrangement of the test equipment.

Active thermography methods can be determined by area of heating, which can be in the form of: a point, a line or all surfaces. Heating the studied object at a point and a permanent scanning of the surface, the temperature is recorded with a certain delay which depends on the depth at which the defect occurs. In particular, this way is helpful for detecting defects located perpendicular to the surface of the tested object. During linear heating, the object warms up in a long narrow strip that moves across the component. On the whole, this method is helpful in the detection of cracks located vertically to the surface of the tested object. However, the most common technique is the heating of the entire surface. All possibilities mentioned above possess advantages and disadvantages, generally associated with the efficiency [8,9,10].

Infrared thermography gives the possibility to investigate and understand many processes where temperature plays a crucial role. Attributes such as speed, contactless and real time measurement, efficiency have resulted in finding applications in a wide variety of disciplines, i.e. in building inspection, control of industrial processes, maintenance of power plants, non-destructive testing, etc.

3. PULSED THERMOGRAPHY

Nowadays, there is a significant increase in the use of pulsed thermography for manufacturing and maintenance applications. This tendency is caused mainly by inspection quickness of this technique and simplicity of data interpretation [14]. Other techniques are costly both in terms of purchase of hardware and software, additionally, they require an experienced researcher to analyze the data and draw correct conclusions, therefore, there is the need to develop this method for more complex geometries (e.g. cylindrical).

The pulsed thermography uses a thermal excitation source to rapidly heat the surface of

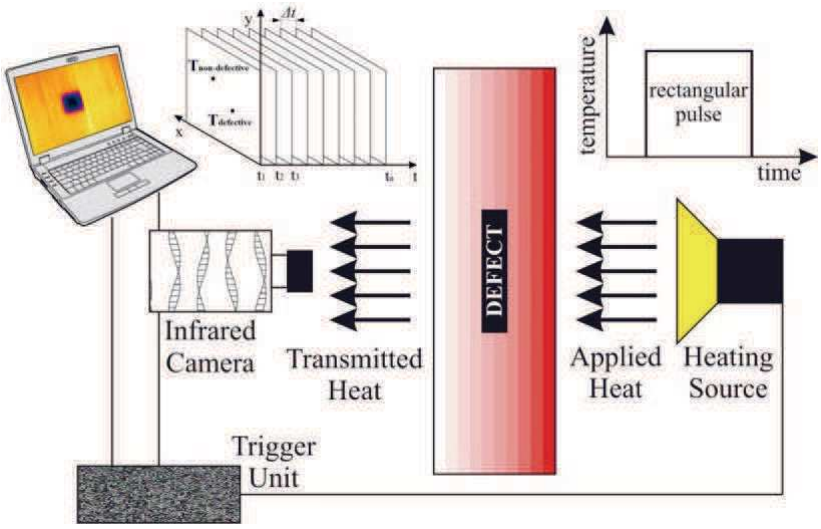

Fig. 1. Principle of the pulsed infrared thermography [8].

the investigated component, then, an infrared camera records a series of thermograms at constant intervals in time domain during both the heating and cooling stages. When the thermal waves reach the defect, it changes its propagation rate, producing a thermal contrast on the surface. Pulsed thermography is an indirect process because subsurface features of a material are inferred by the surface temperature response. It should be noted that the pulse period must be chosen carefully to prevent the failure of an analyzed material. Results are visualized throughout the creation of thermogram sequences which map the temperature distribution on the surface of the examined object. This process is schematically illustrated in Fig. 1.

4. THERMAL CONTRAST

The thermal events occur within defective areas and are caused due to different thermophysical properties of flaws and non-defective material. Heat dissipation is time-dependent therefore it is possible to capture the moment in time when thermal discrepancies are the greatest (Fig. 6). The selection of the defective spot in a structure is based on the indication of the highest thermal contrast both in variable time (i.e. t) and space (i.e. x and y pixels in the thermogram).

There are several definitions used to determine the thermal contrast [9,10,15]. In the present study the absolute thermal contrast was used:

$$T_c = T_{nd} - T_d \text{ [°C]} \quad (1)$$

where T_d is a temperature of the defective region of the specimen, and T_{nd} is the temperature of the non-defective region of the examined specimen. The benefit of computing T_c is not only its simplicity but better visualization of desirable flaws and, what is more important, the quantification of defects. It should be mentioned that the absolute thermal contrast is strongly related to the absorbed energy, hence it is under influence of non-uniform heating and/or fluctuations of surface emissivity. In addition, this situation limits direct comparison of results with other experiments.

5. EXPERIMENTAL STUDY

The examined specimens were manufactured from 8 plies of Hexcel TVR 380 M12/R-glass unidirectional prepreg layers. The geometry of specimens was cylindrical with a nominal thickness of 2 mm, the length of 300 mm and the inner radius of 92 mm (Fig. 2). The laminate had a nominal fiber volume of 60% and the ply thickness of 0.25 mm. To provide compromise between realistic representations and

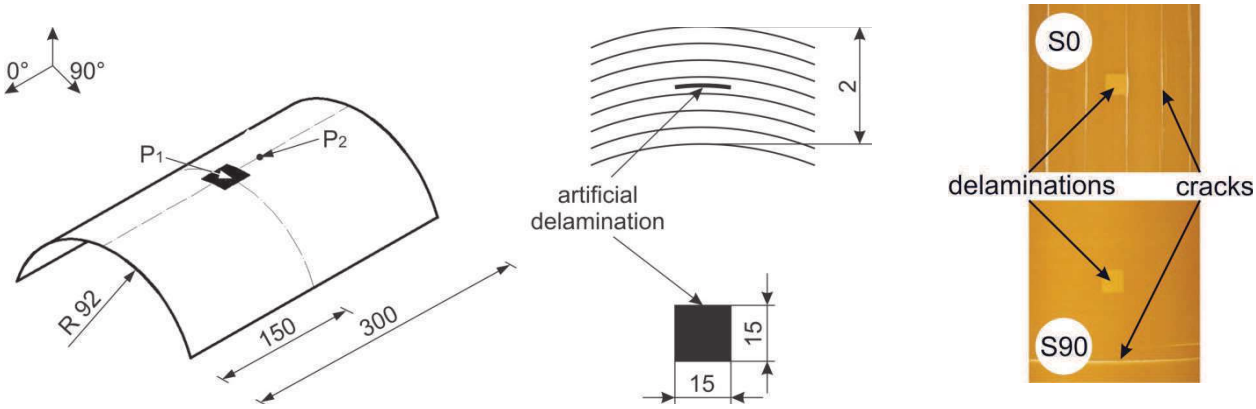

Fig. 2. The geometry of the specimens, location of the artificial delamination and real view.

to ease of preparating the delamination, Teflon film in the form of a single square was introduced during the manufacturing process in the middle of the laminate specimens between the 4th and 5th layers. The position of this insert in relation to the specimen is shown in Fig. 2. The used specimens were previously statically loaded, until final failure occurred. In the presented study both artificial delaminations and mechanical cracks were detected but the current analysis concerns only the delamination.

The system used in this study consisted of a Flir A325 IR camera, a halogen lamp, a computer and a trigger box. The infrared detector works in spectral range from 7.5 to 13 μm with a frame rate of 60 Hz and has a focal plane array pixel format of 320×240. The whole process

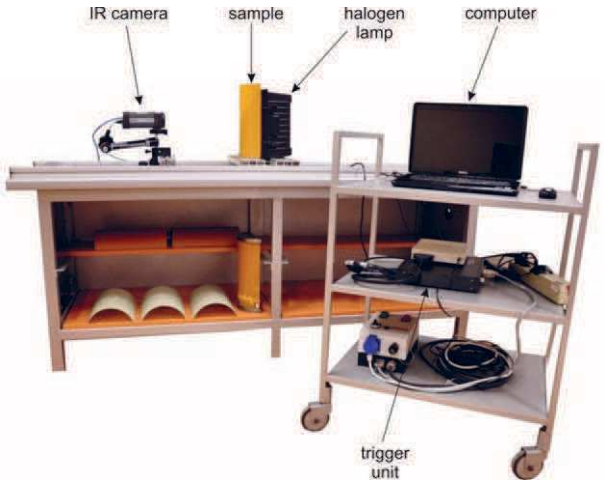

Fig. 3. Experimental setup.

was controlled by using IR-NDT software. The same program was used to process the acquired data. Additional analysis of thermograms sequence was carried out by Researcher Pro software. Fig. 3 presents the complete experimental setup used in the current investigation.

The analysis was carried out in ambient conditions. A single test lasted continuously for 100 seconds, including 10 seconds excitation time of the specimens by halogen lamp. The IR camera and thermal stimulation unit were arranged opposite to each other.

6. RESULTS AND DISCUSSION

The results of the conducted pulsed thermographic analysis were presented in the form of thermograms and graphs for the glass/epoxy samples of two fibers orientations (S0 and S90). The thermograms showed the temperature distributions on the surfaces of the specimens for maximum temperature contrasts.

The artificially defected area was clearly visible on the thermal images in the case of 2D and 3D images as a region with lower temperatures. In addition, for better presentation of the temperature distribution on the investigated surfaces, in the figures and horizontal and vertical temperature profiles were drawn. The temperature profiles also confirmed the existence of the introduced insert. Moreover, on horizontal temperature profiles for the S0 specimen the variable temperature distribution

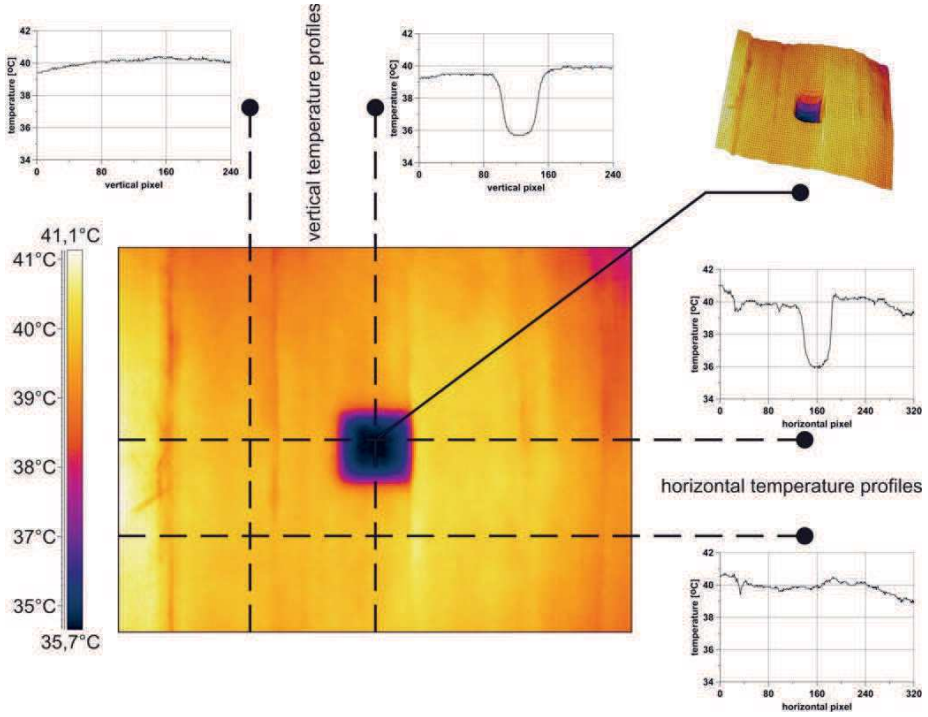

Fig. 4. Thermogram with the horizontal and vertical temperature profiles for S0.

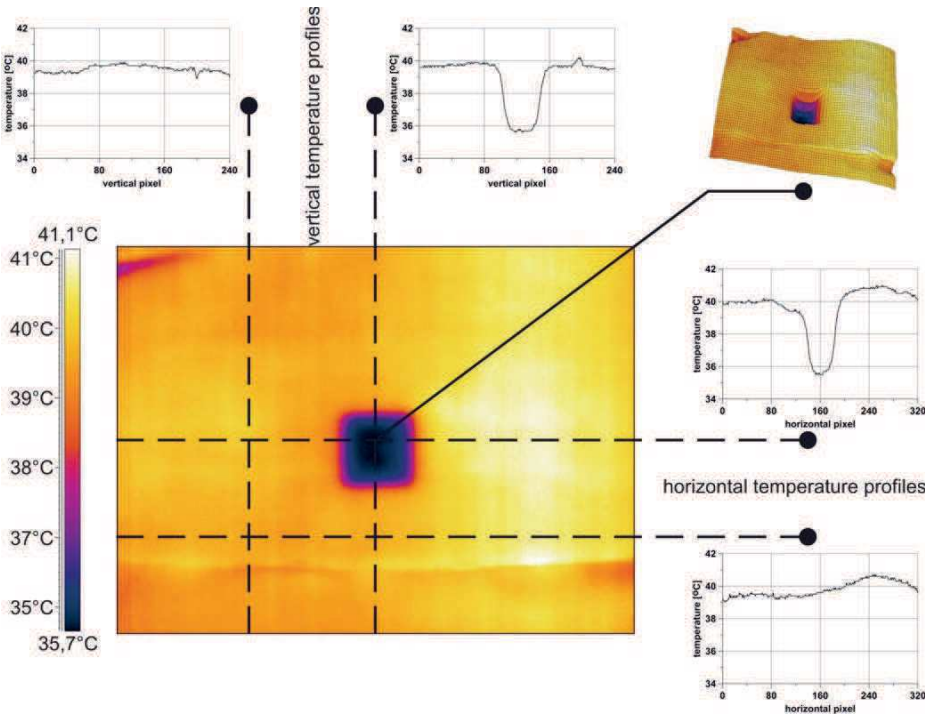

Fig. 5. Thermogram with the horizontal and vertical temperature profiles for S90.

was visible not only in the artificial delamination spot but also for the mechanical cracks which for current settings of research equipment could not be evaluated. Discrepancies in temperature distribution were caused by the combination of several conditions such as

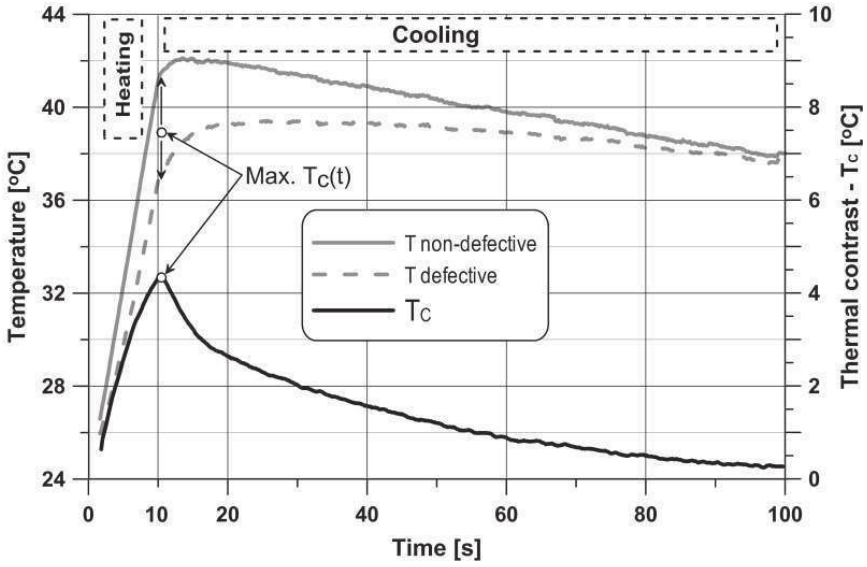

Fig. 6. Temperature distribution and thermal contrast for S90.

non-uniform heating, fluctuation of the surface emissivity, environmental reflections, surface complexity etc.

The temperature distribution discrepancies on the surfaces of the investigated specimens were caused by the different thermal properties of the composite material and the inserted artificial model of the delamination. In essence, owing to these differences, it was possible to reveal subsurface discontinuities. However, real delamination is a void of air with lower thermal conductivity than the widely used model of the delamination in the form of the Teflon foil.

The temperature distributions and the thermal contrast in time domain for the two selected points P_1 and P_2 located on the defective and non-defective area (Fig. 2) were presented in Fig. 6. The maximum temperature contrast equaled 4.42 °C and was observed after the end of heating stage (in 10.33 s). These findings were similar for both investigated specimens (S0 and S90), therefore only representative results were presented in Fig. 6.

7. SUMMARY

In the presented work, thermographic analysis was applied to investigate defective glass/epoxy cylindrical panels. The analysis concerned one particular technique known as Pulsed Thermography, which is widely applied in industry due to its simplicity. The conducted analysis confirmed the usefulness of this method for cylindrical structures with defects – both artificial and mechanical. The presented results focused mainly on the detection of the artificial delamination. The effects of the analysis were presented in the form of thermal images and temperature profiles. As a measure of defect quantification, absolute thermal contrast was applied.

Acknowledgements

The National Science Center Poland (DEC-2013/09/B/ST8/00178) is gratefully acknowledged for financial support.

Literature

[1] Short G.J., Guild F.J., Pavier M.J., *Delamination in flat and curved composite laminates subjected to compressive load,* Composite Structures, 2002, 58, pp 249-258.

[2] Akbarov S.D., *Stability loss and buckling delamination. Three-dimensional linearized approach for elastic and viscoelastic composites,* Springer-Verlag, Heidelberg, Berlin 2013.

[3] Vachon P.L., Brailovski V., Terriault P., *Prediction of the propagation of impact-induced delamination in carbon/epoxy laminates,* Composite Structures, 2013, 95, pp. 227-235.
[4] Muc A., *Mechanika kompozytów włóknistych*, Księgarnia Akademicka, Kraków, 2003.
[5] Kuhn E., Valot E., Herve P., *A comparison between thermosonics and thermography for delamination detection in polymer matrix laminates*, Composite Structures, 2012, 94, pp. 1155–1164.
[6] Lewińska-Romicka A., *Badania nieniszczące. Podstawy defektoskopii*, WNT, Warszawa, 2001.
[7] Almond D.P., Peng W., *Thermal imaging of composites*, Journal of Microscopy, 2001, 201, pp. 163-170.
[8] Pastuszak P.D., Muc A., *Methods of infrared non-destructive techniques: review and experimental studies*, Key Engineering Materials, 2013, 542, pp. 131-141.
[9] Maldaque X.P.V., *Theory and practice of infrared technology for nondestructive testing*. John Wiley & Sons, Inc., New York – Toronto, 2001.
[10] Maldague X.P.V., Moore P.O., *Infrared and thermal testing nondestructive testing handbook*, American Society for Nondestructive Testing, 3, 2001.
[11] Breitenstein O., Warta W., Langenkamp M., *Lock-in Thermography. Basics and use for evaluating electronic devices and materials*, Springer-Verlag, Berlin, Heidelberg, 2010.
[12] Ibarra-Castanedo C., *Quantitative subsurface defect evaluation by Pulsed Phase Thermography: Depth retrieval with the phase*, PhD thesis, University Laval, 2005.
[13] Oliferuk W., *Termografia podczerwieni w nieniszczących badaniach materiałów i urządzeń*, Biuro Gamma, Warszawa, 2008.
[14] Ibarra-Castanedo C., Genest M., Servais P., Maldague X. P.V., Bendada A. H., *Qualitative and quantitative assessment of aerospace structures by pulsed thermography*, Nondestructive Testing and Evaluation, 2007, 22, pp. 199–215.
[15] Benitez H. D., Ibarra-Castanedo C., Bendada A. H., Maldague X., Loaiza H., Caicedo E., *Definition of a new thermal contrast and pulse correction for defect quantification in pulsed thermography*, Infrared Physics & Technology, 2008, 51, pp. 160–167.