PROBLEMY MECHATRONIKI
UZBROJENIE, LOTNICTWO, INŻYNIERIA BEZPIECZEŃSTWA

ISSN 2081-5891 **8, 2 (28), 2017, 43-54**

PROBLEMS OF MECHATRONICS
ARMAMENT, AVIATION, SAFETY ENGINEERING

Infrared Thermography Using Thermal Eddy Current Excitation for Non-Destructive Testing of Multi-Layer Epoxy-Carbon Composites

Waldemar ŚWIDERSKI*, Paweł HŁOSTA

Military Institute of Armament Technology,
7 Prymasa Stefana Wyszyńskiego Street, 05-220 Zielonka, Poland
**Corresponding author's email address: waldemar.swiderski@wp.pl*

Received by the editorial staff on 2 June 2016
Reviewed and verified version received on 23 January 2017

DOI 10.5604/01.3001.0010.1570

Abstract. The eddy current thermography method is a new technique for the non-destructive detection of cracks in materials based on the conduction of an electric current. It is a combination of eddy current testing and thermography. Eddy currents are used to heat the tested sample, while the defect detection is based on changes in the temperature field profile on its surface, as recorded by a thermographic camera. The article discusses numerical modelling methods supporting the thermographic non-destructive testing of composites and presents example results of the tests.
Keywords: mechanics, infrared thermography, multi-layer composite, eddy currents, non-destructive testing

This work has been compiled from the paper presented during the 11th International Armament Conference on Scientific Aspects of Armament and Safety Technology, Ryn, Poland, September 19-22, 2016.

1. INTRODUCTION

Fibre-reinforced composites currently dominate the market of composite materials due to their mechanical and strength properties combined with minimal mass. The fibres used in their production can be continuous (continuous fibres or monofilaments) or non-continuous (staple fibres or whiskers) [1].

The reinforcements used may also include numerous products created from single fibres: roving, mats, fabrics, preimpregnants, and shaped elements [2]. The fibres used in composite reinforcements may be: glass, carbon (graphite), aramid, organic, steel or mineral.

CFRP (Carbon Fibre Reinforced Plastics) are polymers reinforced with carbon fibres, used to produce incredibly strong and very light materials. Its properties mean it is used in the arms industry as a material for constructing light ballistic covers, and in the military aerospace industry as a structural material. All the significant companies in the arms industry currently manufacture personal ballistic protection systems based on fibre reinforced composites [3].

One example of the use of carbon fibre composites based on epoxy resin is the structure of the central part of the aerofoil in the strategic bomber, Stealth B-2 Spirit. Light aircraft structures often use 3D-woven composites, where premoulded multi-layer reinforcements are manufactured, such as in the shape of an I-beam, for the construction of aircraft wings as well as for stiffened panels, keel bundle frames, and formers used in fuselage structures [4]. They can also function as an effective form of protection against radar and thermography [5].

Composites are more at risk of the appearance of defects than other materials, both at the stage of manufacture and during their use. This is particularly influenced by the varying nature of their components. Monitoring the state of materials in engineering designs with the use of non-destructive test methods avoids the destruction of the product as a result of existing defects. The fundamental element in the application of non-destructive methods is the correct interpretation of the obtained information [6].

Industry uses several technologies to manufacture multi-layer composites, but none of them ensures that an ideal structure is obtained. Different issues may occur in its use as a result of a variety of stresses, vibrations and shocks caused by impacts (hard items, bullets, shrapnel, etc.).

The work [7] has a classification of defects, both those based on the technology and those caused by shocks. Those occurring most frequently in multi-layer fibre-reinforced structures are:

- incomplete impregnation of the fibres by surface preparation,
- insufficient or uneven hardening of the resin,
- blisters (of air and other volatile substances),

- voids, i.e. areas between fibres that are not filled with resin,
- delaminations,
- cracks and ruptures of the fibres,
- cracks in the matrix,
- local lack of reinforcement in the matrix.

2. TEST METHOD

The active thermographic methods used in non-destructive testing require a source of thermal stimulation for the material, where the changes in the temperature field on the surface of the tested object make it possible to identify whether there are discontinuities (defects) within the internal structure of the material. One such source of thermal stimulation involves eddy currents [8].

Composite samples that conduct an electric current can be heated by creating eddy currents, achieved by exciting the material with coils. The density of the absorbed thermal radiation is lower than in the case of heating with optical radiation sources, but such induction heating does not cause disturbances as a result of secondary radiation.

The density and the density profile of the eddy currents in the object being tested depend on [9]:

- frequency of the magnetic field used to create the eddy currents,
- distribution of the magnetic field, determined by the configuration, shape and dimensions of the converter,
- shape of the object,
- dimensions of the object,
- electromagnetic parameters of the object, i.e. its electric conductivity and magnetic permeability,
- material, and the structural and geometrical heterogeneities of the object.

The distribution of the eddy currents in the tested object depends on a range of values describing the object. The most significant of these are:

- electrical conductivity γ,
- magnetic permeability μ,
- converter frequency f.

This article continues the work on analysing the potential for the application of this method in the non-destructive testing of materials (metals and their alloys) used in the structures of different craft and vessels [10] as well as light ballistic covers [11]. This article presents a comparison of the results of the computer simulation based on the experimental results.

3. HEAT FLOW MODEL

For non-destructive testing (NDT) of an object, with the use of the thermovision technique to carry out the diagnostic tasks involving estimating the dimensions and the depth of a defect, it is necessary to use an appropriate mathematical model describing the relations between the temporal and spatial temperature distributions and the properties of the object.

The analysis of the properties of the thermovision testing with the use of the selected method was intended to solve the simple and reverse problems of heat conduction. The simple problem consists in searching for a response from the object to the thermal excitation, under specified structural and boundary conditions. The reverse problem consists in reconstructing the object parameters based on a knowledge of the parameters of the thermal excitation and the response of the object.

The heterogeneities in a structure of any kind, including defects, distort the “standard” flow of the heat flux in the object and lead to local temperature anomalies, which are transmitted through the object material to its surface, where they are recorded in the form of temperature signals by the thermovision equipment.

The transitive states of thermal conductivity in the sample defined spatially by a Cartesian three dimensional model were described in the ThermoEdCur program with the following system of equations:

– parabolic heat-conduction equation:

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

– initial condition for the equation:

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

– boundary condition for the front surface:

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

– boundary condition for the back surface:

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

– adiabatic process conditions for lateral surfaces, in coordinates x and y:

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

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

– temperature continuity and heat flux conditions at the layer boundary and between the layers and defects:

$$T_i(x,y,z,\tau) = T_{i\pm1}(x,y,z,\tau) \tag{6}$$

$$K_i^{q_j} \cdot \frac{\partial T_i(x,y,z,\tau)}{\partial q_j} = K_{i\pm1}^{q_j} \cdot \frac{\partial T_{i\pm1}(x,y,z,\tau)}{\partial q_j}$$

with:

T_i – temperature in the *i*-th area determined in relation to the initial temperature of the sample,
T_{in} – initial temperature of the sample,
x, y, z – Cartesian coordinate system,
q_j – determined by coordinate *x, y* or *z* (j = 1÷3),
$\alpha_i^{q_j}$ – thermal diffusivity in the *i*-th area of coordinate q_j,
$K_i^{q_j}$ – thermal conductivity in the *i*-th area of coordinate q_j,
T_{amb} – ambient temperature,
L_x, L_y, L_z – dimensions of the sample.

The geometry of the sample and the defect is presented in Fig. 1. The ThermoEdCur software solves the thermal conductivity equations by applying the numerical finite element method. The development of the ThermoEdCur program was based on the simulations of processes within the scope of non-destructive testing, essential for which are signals corresponding to the transitional surface temperature conditions above the undersurface defects. A unique algorithm was used in ThermoEdCur, making it possible to model very thin defects in thick materials without any loss of calculation accuracy.

It is assumed in the program that both the tested sample and the undersurface defects have parallelepiped shapes (Fig.1). The thermal parameters of the sample and the defects can be determined independently in all three planes of the space, as a result of which these elements can be characterised by full anisotropy. The model assumes that the lateral surfaces of the sample are adiabatically isolated.

On the other hand, temperature continuity is maintained between the boundaries of the sample layers and between the defects and their environment. The programme also includes capacitive defects, which means that, contrary to other models used in non-destructive testing, the calculations take into account both the diffusivity and thermal conduction of the defects. This allows a more accurate description of the thermal phenomena related to the defect and its environment.

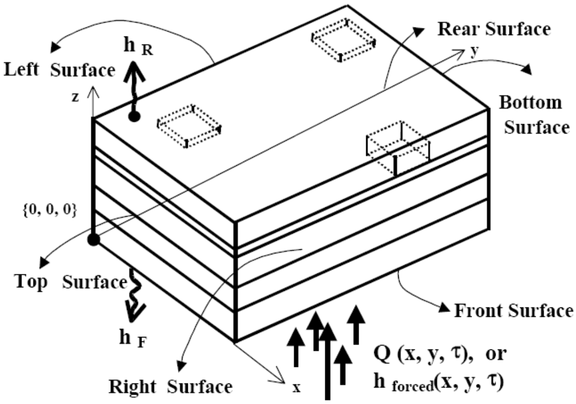

Fig. 1. 3-dimensional sample of composite with undersurface defects, illustrating the pre-determined surfaces

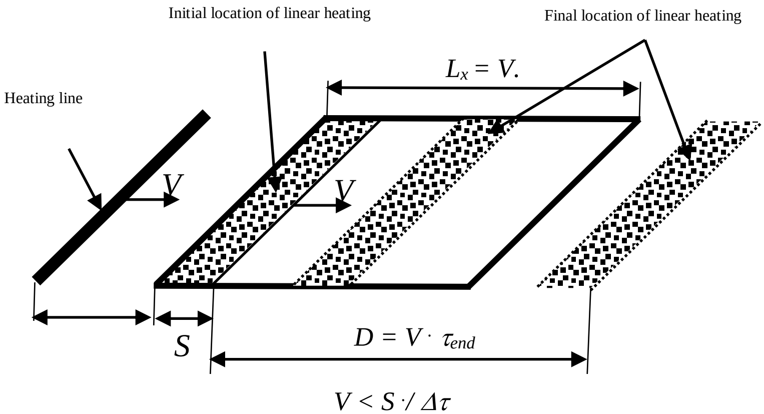

Fig. 2. Linear heating

Figure 2 presents the linear heating law, which is often used in eddy current heating in order to scan the entire surface of an object with uniform heating. The important parameters are the velocity of movement of heating line *V* and the width of line *S*.

4. DEFECT DETECTION SIMULATION

In order to determine the changes in the temperature field on the surface of an epoxy-carbon composite, the ThermoEdCur software was used, as developed by prof. V. Vavilov. The software contains algorithms developed jointly by prof. Vavilov and the authors of the article.

The analysed composite model with defects is presented in Fig. 3. It consisted of two 1 mm carbon fibre sheets connected by a 0.1 mm layer of epoxy resin. Between the sheets (in the resin layer), two thin (0.1 mm) sheet copper defects (D1 and D2) were simulated, with an area of 20 × 20 mm and 10 × 10 mm, as well as two Teflon defects (D3 and D4), of the same thickness and area as for the sheet copper defects. The thermophysical and electrolytic conductivity parameters adopted in the computer simulations are presented in Table 1.

Linear heating with density $Q = 10^6$ W/m^2 generated by means of eddy currents at a frequency of 35 kHz and velocity of heating line movement (with a width of 1 cm) $V = 0.05$ m/s.

Table 1. Material parameters

Material	**Thermal conductivity W/m·K**	**Specific heat J/kg·K**	**Density kg/m^3**	**Electrolytic conductivity S/m**
Carbon composite [12]	0.8	1200	1600	21000 [13]
Epoxy resin [12]	0.2	1700	1300	21000*
Teflon [12]	0.23	1050	2210	$1·10^{-25}$ [14]
Copper [12]	380	380	8900	$5.96·10^{7}$ [14]

**due to a lack of credible information concerning the electrolytic conductivity for epoxy resin, the value was as assumed for a carbon composite*

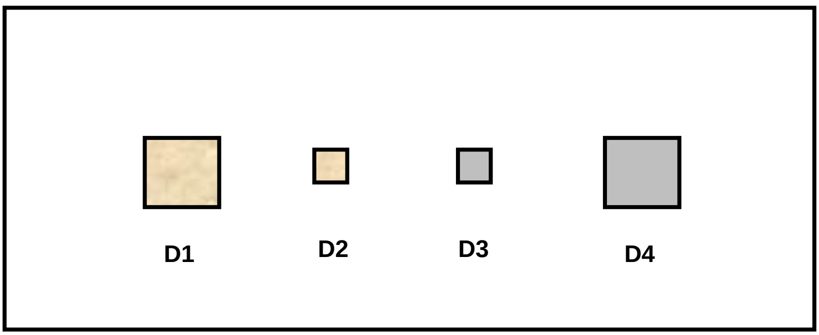

Fig. 3. Model of epoxy – carbon sample with defects

Table 2 presents the results of the defect detection simulation (ΔT – difference in the signal of the surface temperature above the defect and the surface temperature of the sample outside the defect). The results were obtained by means of simulating the heating on the opposite side of the sample from the calculated surface change in the temperature field.

Table 2. Results of the computer simulation

Defect	**ΔT** **°C**
D1	0.81
D2	0.36
D3	- 0.23
D4	- 0.34

5. TESTING

The testing was carried out with the use of infrared thermography in the transmission mode using eddy currents as the source of the thermal excitation for the test sample. The eddy current generator (1) induced eddy currents at a frequency of 35 kHz and power of approx. 100 W. The generator head (2) was manually moved across the sample surface, while on the opposite side of the sample the surface changes in temperature field were measured with a FLIR 7600 SC camera (3). See Fig. 4 for the layout of the equipment.

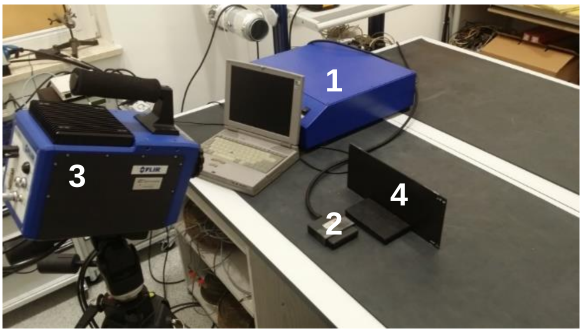

Fig. 4. Experimental set up

The sample (4) was made up of two 1 mm carbon fibre sheets (150 × 350 mm) connected by a 0.1 mm layer of epoxy resin. Six defects were located between the sheets, three made of sheet copper (squares with sides measuring 20 and 10 mm and a disc with a diameter of 20 mm) and three made of Teflon with the same dimensions and shapes.

Figures 5-7 present the a selection of the results of the changes in temperature profile on the surface of the sample above the defects as a result of heating the sample with eddy currents. The influence of the structure of the carbon fibre fabric on the temperature results is clearly visible. For the purpose of better illustration of the magnitude of the temperature changes, and their comparison with the results obtained from numerical calculations, trend lines were drawn.

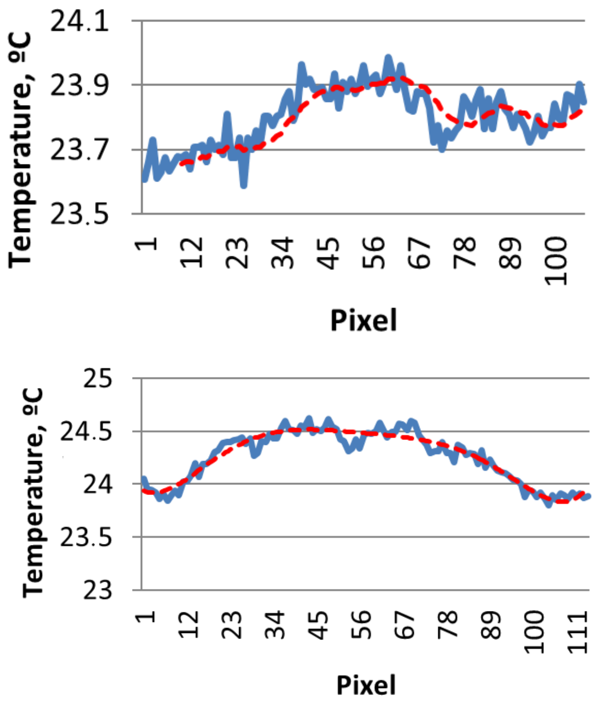

Fig. 5. Surface temperature profile over a sample defect (0.1 mm thick copper square, 20 × 20 mm)

The comparison of the numerical calculations with the experimental results shows that the values obtained from the simulation are higher than the experimental ones. The differences range from approx. 0.15ºC to 0.2ºC, taking into account the values determined by the trend line. The comparison of values determined by single peaks indicates smaller differences.

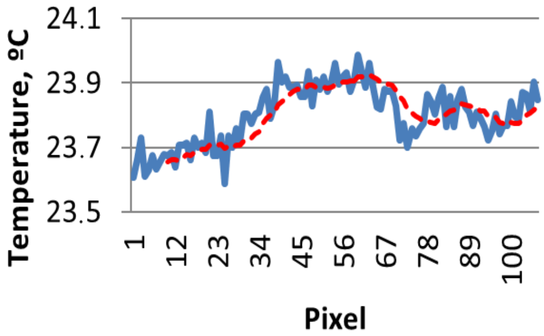

Fig. 6. Surface temperature profile over a sample defect (0.1 mm thick copper square, 10 × 10 mm)

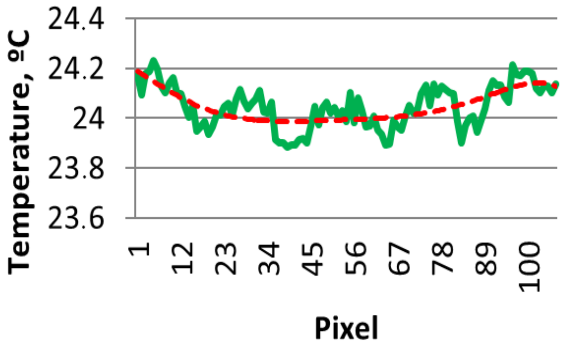

Fig. 7. Surface temperature profile over the sample defect (0.1 mm thick 20 mm Teflon disc)

Figure 8 presents a thermogram of part of the tested sample, where four undersurface defects are visible. Two of them, marked '1' in the figure, are the sheet copper defects (10 × 10 mm square and 20 mm diameter disc), while the same dimensions apply to the two Teflon defects visible in the thermogram, marked '2' in the figure. As shown in the charts (Figs. 5-7) and the thermogram (Fig. 8), the sheet copper defects caused an increase in the temperature on the surface of the sample, whereas the Teflon defects caused a decrease, which was also indicated by the numerical calculations (Tab. 2).

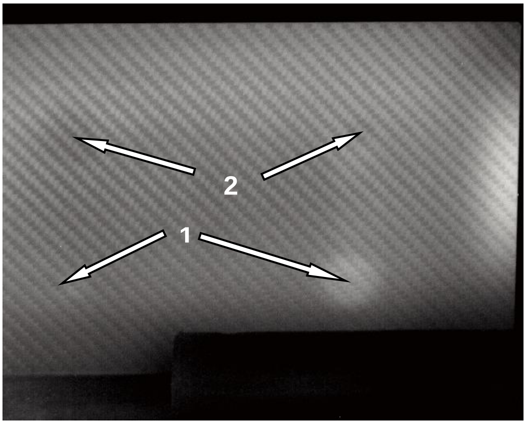

Fig. 8. Thermogram of sample with defects

6. CONCLUSION

The numerical calculations and experimental testing showed that the infrared thermography method with eddy current thermal excitation can be used to detect very thin defects in multi-layer epoxy-carbon composites. Naturally, there is a range of limitations related to the thickness of the tested material, the nature of the defects, the testing procedure and the method of generating eddy currents. It should also be taken into account that this is probably the first work of this type carried out in Poland, and the determination of the limitations of this method requires further research and development studies.

REFERENCES

[1] Rajczyk Marlena, Bartłomiej Stachecki. 2011. Współczesne materiały kompozytowe wybrane kierunki rozwoju nowych technologii. W *Budownictwo o zoptymalizowanym potencjale energetycznym* (Praca zbiorowa pod redakcją Tadeusza Bobki i Jarosława Rajczyka) 202-211. Częstochowa: Wydawnictwo Politechniki Częstochowskiej.

[2] Oczoś E. Kazimierz. 2008. „Kompozyty włókniste – właściwości, zastosowanie, obróbka ubytkowa", *Mechanik* 7 : 579-592.

[3] Fejdyś Marzena, Marcin Łandwijt. 2010. „Włókna techniczne wzmacniające materiały kompozytowe", *Techniczne Wyroby Włókiennicze* 18(1/2) : 12-22.

[4] Konieczny Jarosław. 2013. „Materiały stosowane w konstrukcjach lotnictwa wojskowego", *Armia* 4 (56) : 68-75.

[5] Wilczyński Andrzej. 1996. *Polimerowe kompozyty włókniste*. Warszawa: Wydawnictwa Naukowo-Techniczne.

[6] Kurzydłowski J. Krzysztof, Anna Boczkowska, Jerzy Schmidt, Katarzyna Konopka, Wojciech Spychalski. 2005. „Monitorowanie uszkodzeń w kompozytach metodami nieniszczącymi", *Polimery* 50(4) : 255-261.
[7] Bełzowski Andrzej, Jan Stasieńko, Bogumił Ziółkowski, Anna Kamińska. 2004. „Niektóre kryteria akceptacji defektów w kompozytach na przykładzie laminatu ciętego strumieniem wody", *Kompozyty* 4 : 12.
[8] Świderski Waldemar. 2010. *Metody termograficzne w nieniszczących badaniach materiałów kompozytowych do zastosowań specjalnych*, Monografia habilitacyjna. Zielonka: Wydawnictwo WITU.
[9] Lewińska-Romicka Anna. 1997. *Defektoskopia wiroprądowa. Poradnik*. Warszawa: Biuro Gamma.
[10] Świderski Waldemar. 2015. "Possibility of Defects Detection by Eddy Current Thermography Method in Marine Structures", *Scientific Journals of the Maritime University of Szczecin* 44(116) : 43-46.
[11] Świderski Waldemar. 2015. Possibility of Military Vehicle Composite Ballistic Cover Non-destructive Testing by Eddy Current Thermography Method. In *Proceedings of 19th International Conference*. *Transport Means* 95-98.
[12] Maldague P.V. Xavier. 2001. *Theory and Practice of Infrared Technology for Non-Destructive Testing.* New York: John Wiley-Interscience,
[13] ThermoEdCur, Operation Manual, Innovation Ltd., Tomsk, 2015.
[14] Ha M.S., O.Y. Kwon, H.S. Choi. Improved Electrical Conductivity of CFRP by Conductive Silver Nano-particles Coating for Lightning Strike Protection, In *Proceedings of ICCM, Jeju*.

Termografia w podczerwieni ze stymulacją cieplną prądami wirowymi w badaniach nieniszczących wielowarstwowych kompozytów epoksydowo-węglowych

Waldemar ŚWIDERSKI, Paweł HŁOSTA

Wojskowy Instytut Techniczny Uzbrojenia
ul. Prymasa Stefana Wyszyńskiego 7, 05-220 Zielonka

Streszczenie. Metoda termografii z użyciem prądów wirowych jest nową techniką badań nieniszczących do wykrywania pęknięć w materiałach przewodzących prąd elektryczny. Jest ona połączeniem badań prądami wirowymi i termografii. Prądy wirowe wykorzystane są do ogrzania badanej próbki, a wykrycie defektu oparte jest na zarejestrowanych przez kamerę termowizyjną zmianach rozkładu pola temperatury na jej powierzchni. W artykule omówiono numeryczne metody modelowania wspomagające termograficzne badania nieniszczące kompozytów oraz przedstawiono przykładowe wyniki badań eksperymentalnych.
Słowa kluczowe: mechanika, prądy wirowe, badania nieniszczące, termografia w podczerwieni, kompozyt wielowarstwowy