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COMPOSITES THEORY AND PRACTICE

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DETECTION OF DEFECTS IN COMPOSITE PLATES BY COOLING DOWN THERMOGRAPHY (CDT)

In this work, a novel approach of thermal non-destructive testing of composite structures is presented. Among the widely-known pros and cons of Active Infrared Thermography (AIRT), there is still space for its cognition and development. In general, AIRT is based on heat transfer which is changed by the presence of subsurface flaws, variation of thicknesses, corrosion etc. Internal defects disturb normal heat diffusion within the material due to different thermophysical properties, and the result is variation of the amplitude and phase of the response signal on the surface of investigated objects. Typically, external excitation is performed by different heat sources (i.e. halogen lamps). Application of a thermoelectric module as a heat flux activation source presents clear disadvantages in terms of versatility, but it creates new possibilities of testing components which cannot be heated e.g., due to thermal expansion or space limitation for the excitation source. In addition, this approach provides quick measurement. The investigated samples are previously cooled down by the thermoelectric module, and then they are exposed to a higher ambient temperature. An infrared camera monitors the surface temperature variation both during the cooling and heating stage in order to reveal subsurface flaws. The main aim of this work is to examine the effectiveness of Cooling Down Thermography (CDT) to detect artificial delaminations in composite plates.

Keywords: Cooling Down Thermography (CDT), fibrous composites, subsurface defects

DETEKCJA USZKODZEŃ W PŁYTACH KOMPOZYTOWYCH ZA POMOCĄ TERMOGRAFII OCHŁADZANIA (CDT)

Zaprezentowano innowacyjne podejście w termicznych badaniach nieniszczących struktur kompozytowych. Wśród powszechnie znanych zalet i wad metod termografii aktywnej istnieje nadal dużo miejsca do ich poznania i rozwoju. Generalnie, omawiane techniki oparte są na transporcie ciepła, który może być zaburzony poprzez defekty podpowierzchniowe, zmiany grubości, korozję etc. Wewnętrzne uszkodzenia zmieniają normalną dyfuzję cieplną w materiale z powodu różnych właściwości termofizycznych, czego wynikiem są zmiany w amplitudzie i fazie sygnału odpowiedzi na powierzchni badanych obiektów. Zwykle jako źródło ciepła używane są lampy halogenowe. Zastosowanie ogniwa termoelektrycznego do ochładzania próbki wykazuje wyraźne wady z punktu widzenia wszechstronności, tworzy jednak nowe możliwości badania komponentów, które nie mogą być ogrzewane, np. z powodu rozszerzalności cieplnej lub ograniczeń przestrzeni niepozwalających na zastosowanie źródła wzbudzenia cieplnego. Ponadto takie podejście zapewnia dużą szybkość pomiaru. Badane próbki są początkowo ochładzane za pomocą ogniwa termoelektrycznego, a następnie ogrzewane przez temperaturę otoczenia. Kamera termowizyjna monitoruje temperaturę powierzchni zarówno podczas chłodzenia, jak i ogrzewania próbki, aby ujawnić uszkodzenia podpowierzchniowe, które zmieniają przepływ ciepła w materiale. Głównym celem tej pracy jest zbadanie efektywności metody termografii ochładzania (CDT) do detekcji sztucznej delaminacji w płytach kompozytowych.

Słowa kluczowe: termografia ochładzania, kompozyty włókniste, defekty podpowierzchniowe

INTRODUCTION

Non Destructive Testing (NDT) involves inspecting methods used to investigate objects without reducing their functional properties. The aim of NDT is to obtain required information about discontinuities, physical or mechanical properties etc. [1]. Among the existing classical NDT techniques such as C-Scan ultrasonic or X-Rays, Infrared Thermography (IRT) emerged as a fast, non-contact and accurate method for assessing and monitoring subsurface flaws. Furthermore, the development of cracks can be also inspected. There are two approaches in IRT: passive and active. In the first case, the temperature of the region of interest is naturally higher or lower than the background, in contrast to the second possibility where it should be externally induced to produce a thermal contrast between the feature of interest and the background [2, 3]. Internal defects disturb the normal heat transfer of the applied energy due to different physical properties, which results in variation of the amplitude and phase of the response signal at the surface of the investigated object, therefore in order to reveal hidden defects by Active Infrared Thermography, a dynamic temperature field should be generated. Typically, external excitation is performed with optical devices such as photographic flashes or halogen lamps but it can also take the form of, for instance, warm or cold air or mechanical oscillations [4, 5]. The application of a thermoelectric module as an excitation source creates new possibilities of testing materials which cannot be heated, e.g., due to thermal expansion or space limitation. In addition, this approach provides quick measurement. The materials investigated in this work have found a wide range of applications in industry, mainly due to their high mechanical properties: specific strength and stiffness. Additionally, it is possible to manage these properties in order to obtain different directional features. This aspect creates new opportunities for the optimal design of modern structures but it is also connected with the assumed load parameters, operating conditions and the possibility of failure occurrence, such as fibre breakage, fibre debonding, matrix cracking or delamination [6]. The listed defects of anisotropic materials can arise from the manufacturing process or subsequent maintenance, resulting in significant reduction of their mechanical properties, therefore, the necessity to detect and evaluate the mentioned flaws to improve the reliability and design of the modern structures is highly desirable. In addition, the presence of cracks in composite structures increases their manufacturing costs and/or elongates the out of service time [7].

THEORETICAL BASIS

Heat diffusion through a solid, where there is no internal heat generation, is a complex 3D problem that can be described by Fourier's law of heat diffusion (or heat equation):

$$\frac{\partial T}{\partial t} = \frac{\lambda}{\rho C_p} \nabla^2 T \tag{1}$$

where $\alpha = \lambda / \rho C_p$ [m^2/s] is the thermal diffusivity of the material being inspected, λ [W/mK] is the thermal conductivity, ρ [kg/m^3] its density and C_p [J/kgK] its specific heat at constant pressure.

For simple cases it is possible to find an analytical solution of this equation. When an investigated 3D object has complex geometry and a non-homogeneous structure, it is necessary to use the numerical solution of Fourier's law of heat diffusion. One of the suitable methods is the finite element method - FEM.

The thermal diffusivity of composite materials is inherently anisotropic. Thus the thermal conductivity tensor was used, assuming that the density and specific heat of the material are constant:

$$\frac{\partial T}{\partial t} = \frac{1}{\rho C_p} \begin{bmatrix} \lambda_{XX} & \lambda_{XY} & \lambda_{XZ} \\ \lambda_{YX} & \lambda_{YY} & \lambda_{YZ} \\ \lambda_{ZX} & \lambda_{ZY} & \lambda_{ZZ} \end{bmatrix} \begin{bmatrix} \dfrac{\partial^2 T}{\partial x^2} \\ \dfrac{\partial^2 T}{\partial y^2} \\ \dfrac{\partial^2 T}{\partial z^2} \end{bmatrix} \tag{2}$$

To obtain the thermal behavior of a specimen submitted to a thermal impulse, a thermograph with an infrared camera is used [8]. This impact is created by heat flux forced by the thermoelectric module. It is assumed that the thermal impulse is a Dirac pulse uniformly applied to the surface of a semi-infinite body [9].

The one-dimensional solution of the Fourier equation for a Dirac delta function in a semi-infinite isotropic solid is given by [10-12]:

$$T(t) = \frac{Q}{e\sqrt{\pi t}} \tag{3}$$

where Q is the energy per unit area and e is the thermal effusivity defined by $e = \sqrt{\lambda \rho C_p}$.

The differential absolute contrast (DAC) method [5] based on the 1D solution of the Fourier diffusion equation can be used. In this method, instead of looking for a non-defective area, the T_{nd} temperature at time t is computed locally assuming that on the first few images of the inspected thermograph, the specified point behaves as a non-defective region. The research described in this paper is a novel approach to the DAC method of examining materials. Instead of using heat flux generated by a heat source, a heat sink is applied. A thermoelectric module creates a heat flux directed through the examined specimen to the module. Any delamination in the analyzed specimen creates a barrier for the heat flux. Thus on a thermographic image, a thermal difference can be observed and the Absolute Thermal Contrast can be calculated.

THERMAL CONTRAST

Thermal contrast is a basic measure used in thermal non-destructive testing and evaluation (TNDT&E) for defect detection and quantification. Subsurface events occurring in the investigated object can be identified due to temperature differences (ΔT) on the surface. This simplest case can be described quantitatively by Absolute Thermal Contrast (ATC). It is schematically illustrated in Figure 1.

When there are small discrepancies between the defective and non-defective areas, it is necessary to enhance the image quality. It can be done by applying other thermal contrast definitions [2]. In this study, the following formula of Running Thermal Contrast (RTC) was used:

$$RTC(t) = \frac{T_d(t) - T_{nd}(t)}{T_{nd}(t)} \quad (4)$$

where T_d is the temperature of the defective region of the specimen and T_{nd} is the temperature of the non-defective region of the examined specimen.

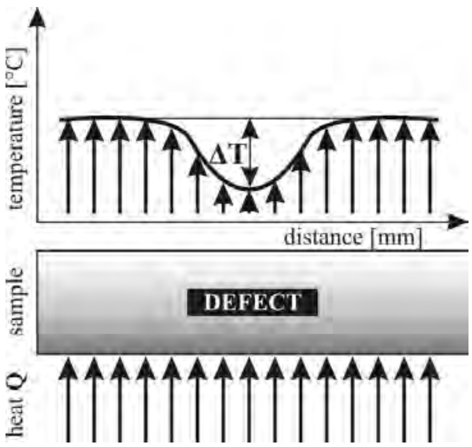

Fig. 1. Absolute thermal contrast

Rys. 1. Absolutny kontrast termiczny

All these temperature contrasts are strongly affected by non-uniform energy excitation and/or emissivity fluctuations. Moreover, the reference region must be defined either automatically or by an operator, which in consequence increases the final measurement uncertainty. Therefore, attempts to create defect detection algorithms which do not require identification of the damage-free region were undertaken.

PULSED THERMOGRAPHY

Pulsed thermography uses an energy excitation source to rapidly induce the surface of the investigated material, then an infrared camera records a series of thermograms at constant intervals in the time domain, both during the heating and cooling stages. When the thermal waves reach the defect, they change their propagation rate, producing thermal contrast on the surface. Pulsed thermography is an indirect process because the 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 failure of the analyzed material.

The results are visualized throughout the creation of the thermal images (thermograms) sequence which maps the temperature distribution on the surface of the examined object in the time domain. This process is schematically illustrated in Figure 2. Among the broad possibilities of pulsed thermography applications, it is also important to determine the limitations of this method.

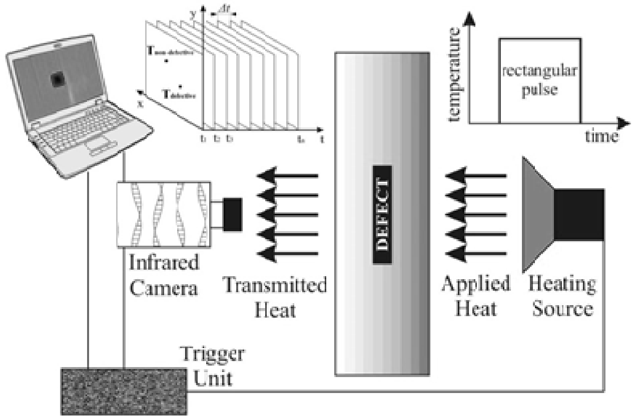

Fig. 2. Principle of pulsed infrared thermography [13]

Rys. 2. Zasada impulsowej termografii w podczerwieni [13]

EXPERIMENTAL PROCEDURE

The system used in this investigation consists of a Flir A325 camera with a maximal frame rate of 60 Hz and a focal plane array pixel format of 320x240, a thermoelectric module with a power supply connected to a trigger box and a computer. The entire process is controlled by using IR-NDT software. The same program is used to process the acquired data. Figure 3. presents the experimental test stand used in the current study.

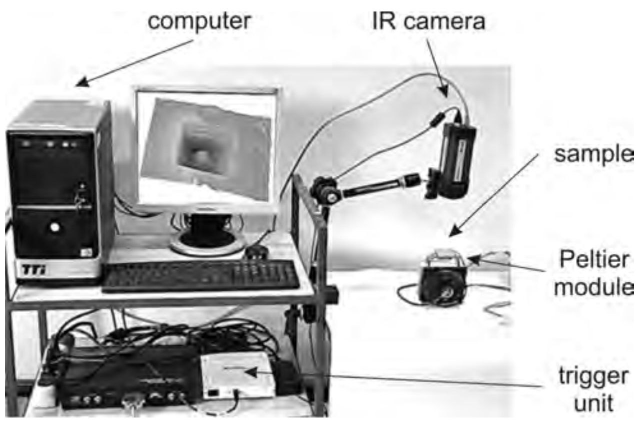

Fig. 3. Test rig

Rys. 3. Obwód badawczy

Specimens

The tested material is a composite woven roving glass/epoxy resin. The specimens were manufactured from 8 layers. The geometry of the samples is a square with the average thickness t_c = 2.64 mm and length L = 50 mm. To provide a compromise between realistic representation and ease of preparation of the defect, Teflon film with a thickness of 200 μm in the form of a single square with the length of 10 mm was introduced during the manufacturing process in the middle of the laminate specimens between the 4th and 5th layer. The location of the embedded delamination is presented in Figure 4.

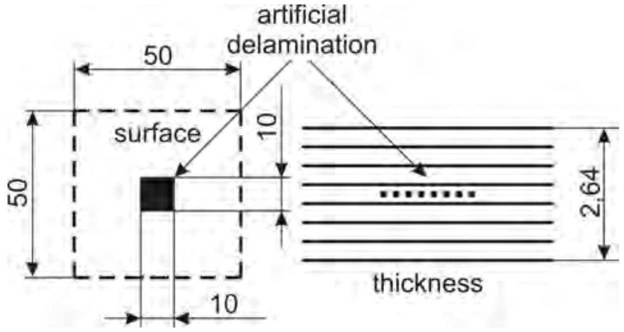

Fig. 4. The geometry of investigated specimens

Rys. 4. Geometria badanych próbek

Test procedure

In this approach to TNDT, a sink of thermal energy is applied. One of these sinks is the commercial TEC1-12710 (50 W) thermoelectric module (Fig. 5). With a voltage applied to it, it creates a temperature difference between the 'hot' and 'cold' side of the module. Therefore, the temperature of the 'cold' side can be lower than ambient temperature. The heat flux flows through the examined specimen to the thermoelectric module. An infrared camera monitors the surface temperature both at the cooling and heating stage. Subsurface flaws can be revealed by thermal contrast between the defective and non-defective zones. The working time of the thermoelectric module was 10 s at the beginning and the total analysis lasted 100 s.

a)

b)

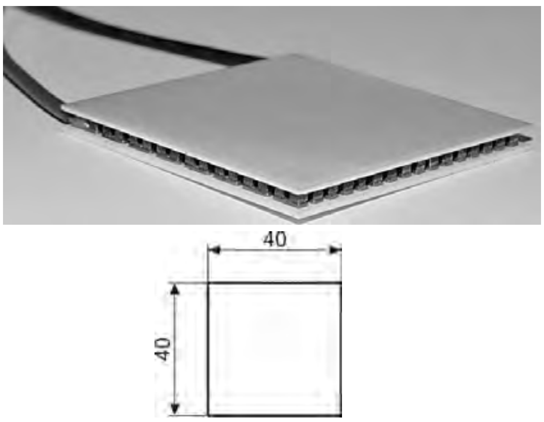

Fig. 5. Thermoelectric module TEC1-12710: a) real view, b) dimensions in millimeters

Rys. 5. Moduł termoelektryczny TEC1-12710: a) widok rzeczywisty, b) wymiary podane w milimetrach

RESULTS AND DISCUSSION

This work was devoted to the detection and localization of an artificial delamination by cooling down thermography. By using an infrared camera, the temperatures on the surface of the defective and non-defective areas were obtained. Figure 6 shows the representative 3D thermogram obtained during the cooling of the specimens with the inserted defect. In the thermal image the shape of the artificial delamination can be recognized.

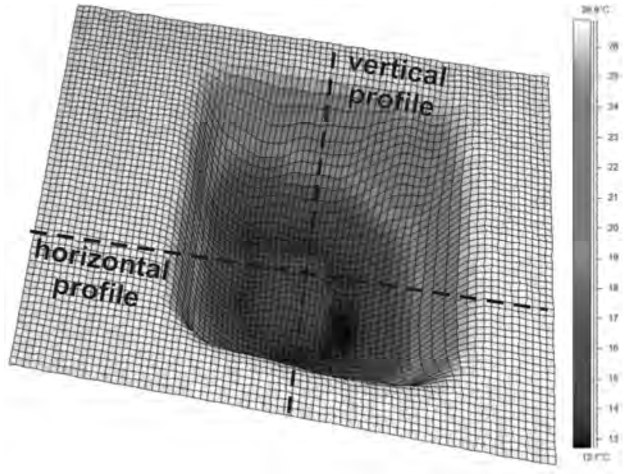

Fig. 6. 3D Thermogram of specimen with artificial defect

Rys. 6. Termogram 3D próbki ze sztucznym defektem

The temperature distribution on the surface of the investigated specimen in the defective and non-defective areas and RTC with time are shown in Figure 7.

a)

b)

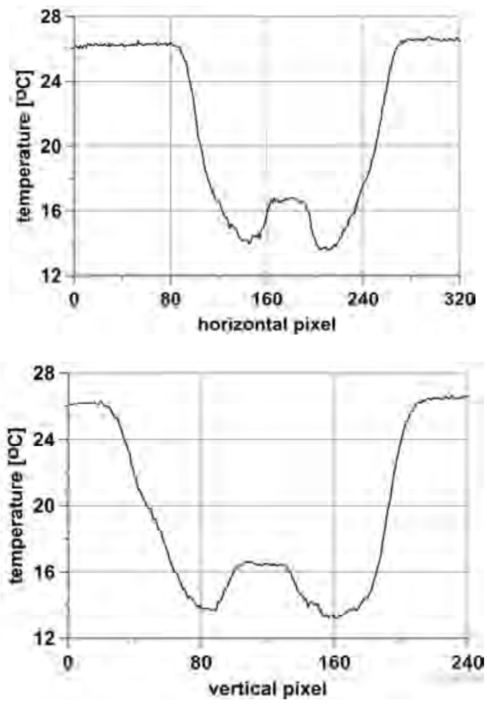

Fig. 7. Horizontal (a) and vertical (b) pixel profiles for maximal temperature contrast of representative thermal image

Rys. 7. Poziomy (a) i pionowy (b) profil temperaturowy dla maksymalnego kontrastu temperaturowego reprezentatywnego obrazu termicznego

The damaged zone acts as a barrier for the heat flux, hence the temperature of this spot is higher than the surrounding area. The RTC factor grows not only during the excitation time of the thermoelectric module but also 2-3 seconds after the voltage is cut (10 s). This is caused by the thermal inertia of the thermoelectric module. A phase shift between the temperature distribution of the defective and non-defective areas can be also observed (Fig. 8). This is due to the different physical properties of composite material and artificial delamination. In the second stage, when the specimen is heated by ambient temperature, the RTC factor drops down below zero due to thermal inertia of the material.

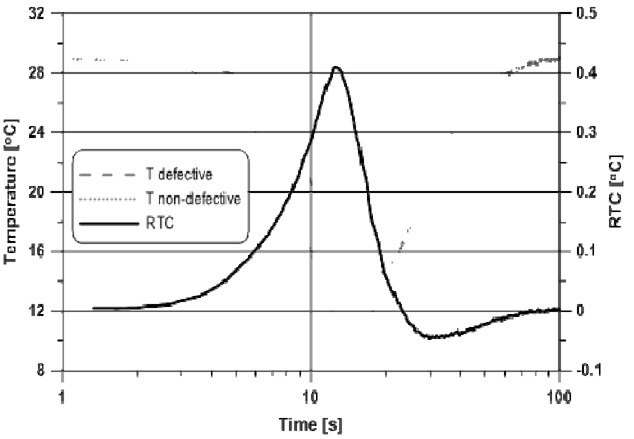

Fig. 8. Temperature variations and RTC versus time

Rys. 8. Zmiany temperatury i RTC w funkcji czasu

CONCLUSIONS

In this paper the development of a real-time, non-invasive technique using pulsed infrared (IR) thermography with a new excitation source is described. The experimental results demonstrated that thermographic analysis is an effective method for revealing defects in composite materials. The specimen area with the defect shows a higher temperature than the area without the defect. Running Thermal Contrast is a good measure of an examined specimen because it is less affected by surface optical properties. The main drawback of the presented method is the need for good contact between the thermoelectric module and the investigated specimen. Summarising the research presented in this paper, Cooling Down Thermography can be a good alternative among NDT techniques. Future work will concern numerical investigation and comparison with the experimental results.

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