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Non-Destructive Testing of Carbon Fiber Reinforced Plastic by Infrared Thermography Methods

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Abstract**—**Composite materials are one answer to the growing demand for materials with better parameters of construction and exploitation. Composite materials also permit conscious shaping of desirable properties to increase the extent of reach in the case of metals, ceramics or polymers. In recent years, composite materials have been used widely in aerospace, energy, transportation, medicine, etc. Fiber-reinforced composites including carbon fiber, glass fiber and aramid fiber have become a major structural material. The typical defect during manufacture and operation is delamination damage of layered composites. When delamination damage of the composites spreads, it may lead to a composite fracture. One of the many methods used in non-destructive testing of composites is active infrared thermography. In active thermography, it is necessary to deliver energy to the examined sample in order to obtain significant temperature differences indicating the presence of subsurface anomalies. To detect possible defects in composite materials, different methods of thermal stimulation can be applied to the tested material, these include heating lamps, lasers, eddy currents, microwaves or ultrasounds. The use of a suitable source of thermal stimulation on the test material can have a decisive influence on the detection or failure to detect defects. Samples of multilayer structure carbon composites were prepared with deliberately introduced defects for comparative purposes. Very thin defects of different sizes and shapes made of Teflon or copper having a thickness of 0.1 mm were screened. Non-destructive testing was carried out using the following sources of thermal stimulation, heating lamp, flash lamp, ultrasound and eddy currents. The results are reported in the paper.

Keywords**—**Non-destructive testing, IR thermography, composite material, thermal stimulation.

I. Introduction

ENGINEERING materials are a class of technical materials which do not occur in nature. They are produced using raw materials available in nature, adapting them to specific technical needs. This group of materials includes non-metallic composite materials [1]. Due to their strength and low weight compared to metals, they are increasingly being used in various applications, both civilian and military. Composite materials reinforced with fibers manufactured in the form of laminates are the basic materials in this family, and they are used to provide increased static and fatigue strength. These materials are obtained by incorporating fibers which are tough, rigid, but usually brittle, into a soft but ductile matrix. The composite materials in this group may possess high mechanical properties at both room temperature and at elevated temperature. The most commonly used fiber reinforced materials are laminates reinforced with carbon fibers and glass, and also aramid fibers in military applications. The beginning of the development of these materials began during the Second World War, when glass fibers were widely produced. The next stage in their development was related to the discovery of carbon fibers in the 1950s. Further development of these composites led to the appearance of aramid fibers, known by their trade name, 'Kevlar' [1].

The most common types of damage which occur in fiber-reinforced laminates are delamination, macro-cracks, cracked fibers, interfacial cracks, micro-cracks, porosity, inclusions, thermal damage, moisture, surface ridges and wrinkles. Delamination damage of layered composites is the typical defect during manufacture and operation which results in a reduction of material strength, rigidity and affection of structural integrity. [2] The most effective methods of non-destructive testing (NDT) to detect damage in laminates are interferometry and infrared thermography [3]. In multilayer structures comprised of laminates, where external damage arises by mechanical injury, the dimensions of the surface defect are different in each individual layer of the composite. This is related to the absorption of the kinetic energy of an impact by individual layers of the laminate. Interlayer destruction occurs due to cracking of the material and stretching of the fibers.

II. Infrared Thermography

NDT procedures using infrared thermography can be divided into passive and active methods [4], [5]. In the passive method, the test object is characterized by a temperature field created during its ordinary functioning. Therefore, passive methods are primarily used for the NDT of devices or their components during operation or shortly thereafter, when excessive differences in temperature distribution on the surface of a test object may indicate the presence of defects. As a result of mechanical or thermal loads occurring during the functioning of the test object, defects radiate or absorb thermal energy, allowing their passive detection using this method.

In the active method, an external source of thermal stimulation (heating or cooling) is applied to the object. Defects in test materials designed before the testing which have a uniform temperature equal to ambient temperature, do not generate 'useful' temperature signals, and for this purpose require heating or cooling of the entire (or at least part of the) object. This testing creates a dynamic temperature field and the results of its distribution depend on the observation time.

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Such active methods are typically used in conjunction with special procedures for data processing.

In work [4] (Fig. 1) is shown the following main NDT methods of active thermography:

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

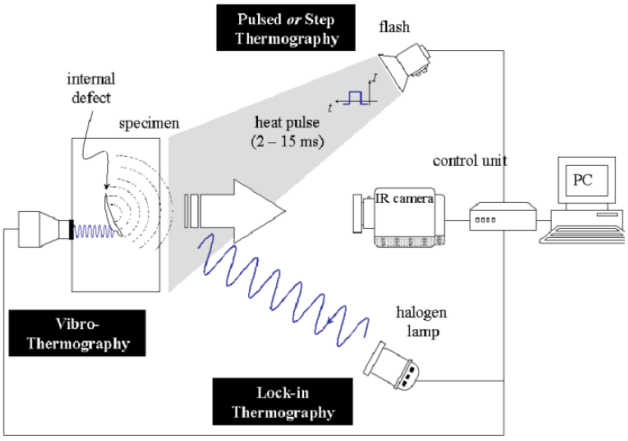


Fig. 1 IR thermography methods – set-up [6]

Pulsed thermography is one of the most popular methods used in the NDT of composite materials. Such testing involves the use of lamps, lasers, *etc.*, in order to generate a pulse (or a series of pulses) of heat force which takes from a few milliseconds to pass through a material of high thermal conductivity (e.g. metal) to a few seconds in the case of materials having low conductivity. A cooling pulse can also be used on the surface of the object (e.g. a flow of cold air, liquid nitrogen, etc.). Pulsed thermography may be implemented in both reflection and transmission modes. A sequence of images (thermal images known as 'thermograms') is recorded with a constant interval between the images, and the object is then cooled to ambient temperature after switching off the radiation source. During the cooling phase, the temperature distribution on the surface of the test object is determined. Depending on the thermal characteristics of the test material, zones of higher or lower temperatures at the surface will indicate the areas in which there may be material defects. Often, to identify areas with defects, it is necessary to use special thermogram processing techniques.

In contrast to the pulsed thermography method, in the method using step heating to stimulate the thermal heating of the object, changes in the temperature distribution on the surface are monitored during both the heating and cooling phases. [7] The energy density used to thermally stimulate the test object is lower than that of the pulsed method. The relatively slow heating rate assists in the testing of a multi-layered structure (e.g. one containing ceramics), also helping to evaluate the connections between layers, detect hidden corrosion in composite aircraft structures, and characterize and evaluate the thickness of the layers.

In the lock-in thermography method (also known as 'synchronous', 'modulation' or 'thermal wave' thermography [4]), the thermal excitation of the object is achieved using the harmonic flow of heat. Thermal stimulation of the object is sinusoidal; based on the known frequency of the excitation signal, the registered system response can be determined by its amplitude and phase angle (amplitude and phase images). [8], [9]

The term 'vibrothermography' was coined in the 1990's to describe the thermal testing procedures designed to assess the hidden heterogeneity of structural materials based on surface temperature fields during cyclical mechanical loading. [10] A similar procedure can be realized by excitation of the material with sound/ultrasonic waves, as the internal friction of the wall defect resulting from the corresponding mechanical excitation leads to increased local temperature. If the loading cycle does not exceed the flexibility of the material and the rate of change is large, the heat loss due to thermal conductivity is small and after loading, the test object returns to its original shape and temperature.

In recent years, there has been great interest in the use of eddy current thermography, wherein the heating of the test samples was achieved through the use of eddy currents (Fig. 2). Eddy current thermography is a new NDT technique that uses pulses of eddy currents inducted in electrically conductive materials to generate local heating inside testing material. This method is based on the changes of the induced eddy current flows revealed by thermal visualization using an infrared camera. [11], [12]

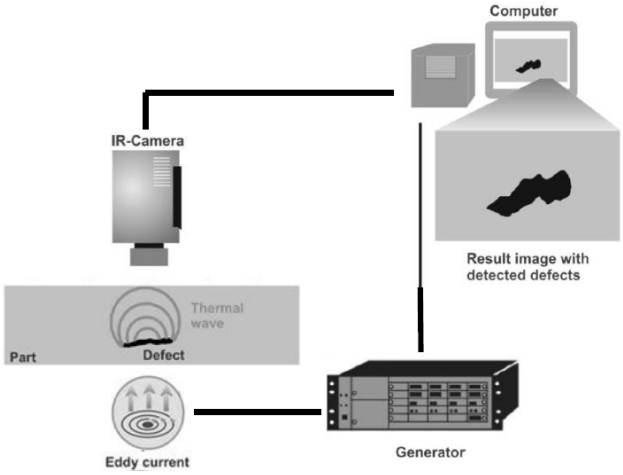


Fig. 2 Eddy current IR thermography – set-up

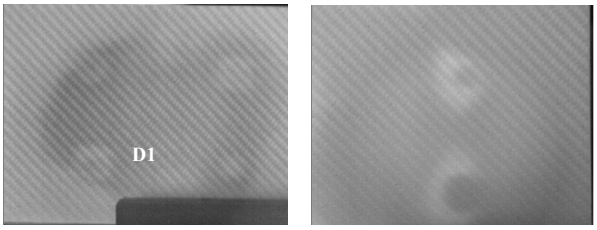
III. Experimental Testing

The test sample (Fig. 3) was made of two plates of carbon fiber (150 × 350 mm), having a thickness of 1 mm, connected to a layer of epoxy resin, having a thickness of approximately 0.1 mm. Six defects were placed between the plates: three copper sheets (two squares with lengths of 20 and 10 mm and a circle with a diameter of 20 mm) and three Teflon sheets of the same dimensions.

Experimental tests were carried out using all of the methods described above. Changes of temperature field on the surface

of the tested samples were recorded by an FLIR SC 7600 infrared camera.

Fig. 3 The test sample



(a) (b)

Fig. 4 The thermograms obtained by pulsed thermography method

During the experiments using the pulsed thermography method, a thermal pulse power of 6 kJ with a duration of 5 ms was generated by a flash lamp. Changes in the temperature field on the heated surface of the sample were registered by an IR camera in sequences consisting of 500 images with a resolution of 640 × 512 pixels, recorded at a frequency of 25 Hz.

For the step heating method, the sample was heated using a heating lamp with a power of 1 kW and for a duration of 5 seconds. The changes of temperature field were recorded during the heating and cooling phases for 20 seconds at a frequency of 0.5 Hz.

The sample was investigated by using a lock-in measuring set made by the Automation Technology Company.

Continuous ultrasonic stimulation was performed with a piezoelectric unit at a frequency of 35 kHz with the power ranging from 80–130 W (the maximum allowed power was 2 kW). The ultrasonic signal was generated for 5 s.

The experiments of eddy current IR thermography were carried out using an IR camera (image format 640 × 512 pixels, acquisition frequency 5 Hz, up to 1600 images in a sequence). The eddy current stimulation was performed with a power ranging from 80–150 W.

IV. Results

Selected experimental results are presented in the graphs and thermograms shown in Figs. 4–11. As shown in the thermograms, all defects have been detected by the methods applied in the experimental testing.

In the graphs shown in Figs. 5, 7, 10 and 11 are exemplified temperature changes on the sample surface over the defect made of Teflon with dimensions of 20 × 20 mm (labelled in the thermograms as D1). The measured temperature changes over the defect D1 are between -0.2 K for pulsed thermography (Fig. 5) to 1.5 K for ultrasonic thermography (Fig. 11).

Shown in Fig. 7 are results from the step heating method obtained for a sharp scratch defect on the back of the sample material (without the artificial Teflon or copper defects).

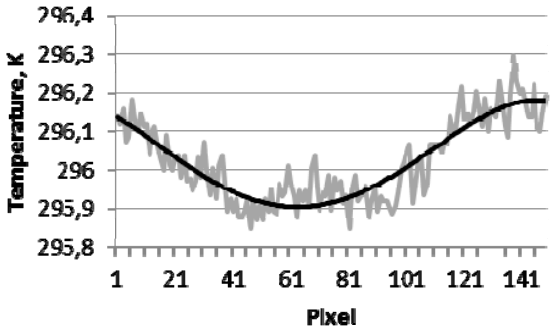
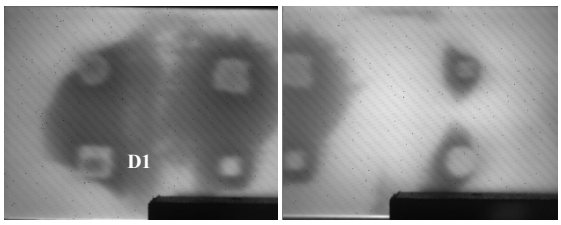


Fig. 5 Temperature change over the defect D1 – pulsed thermography method



(a) (b)

Fig. 6 The thermograms obtained by step heating method

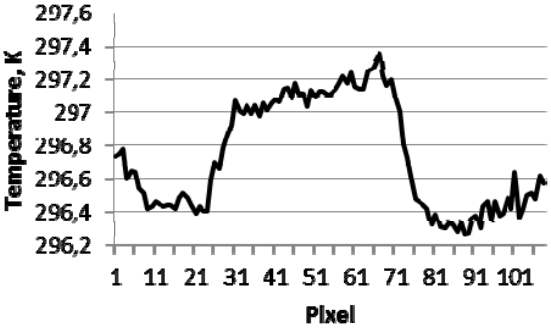
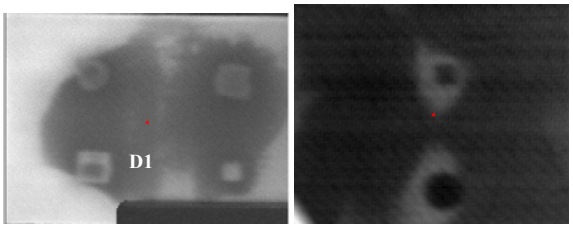


Fig. 7 Temperature change over the defect D1 – step heating method



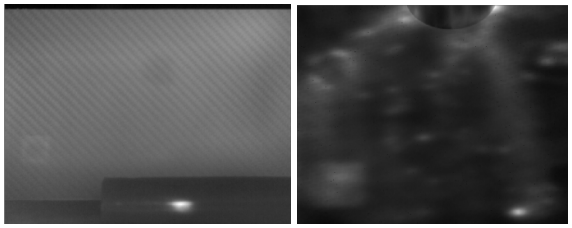
(a) (b)

Fig. 8 The thermograms obtained by lock-in thermography method

On the thermogram generated from the use of ultrasound thermography (Fig. 9 (b)), besides the defects, many small

inhomogeneities are visible, resulting from the structure of the composite (carbon fabric weaves). This may make the identification of small defects difficult. Using a different frequency to the ultrasound used in these testes could probably lead to weakening of the signals.

The test samples in the thermograms are presented in two parts marked in Figs. 4, 6, 8 and 9 as (a) and (b).



(a) (b)

Fig. 9. The thermograms obtained by (a) eddy current thermography, (b) ultrasonic thermography

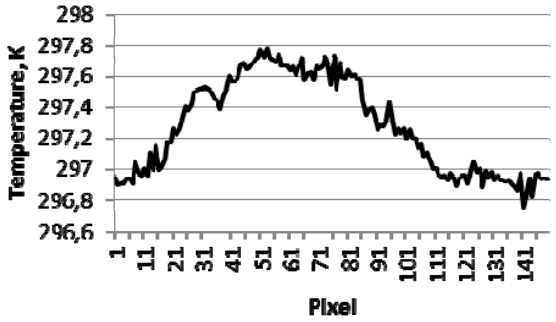


Fig. 10 Temperature change over the defect D1 – eddy current thermography method

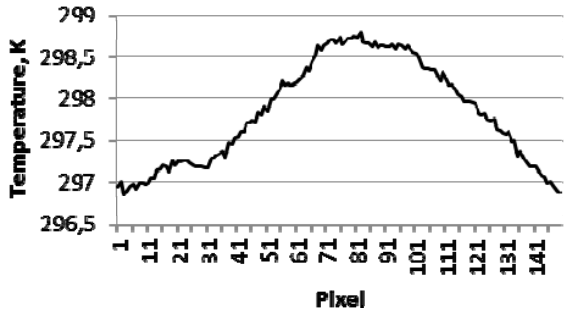


Fig. 11 Temperature change over the defect D1 – ultrasonic thermography method

V. Conclusions

The experimental testing described here has shown and confirmed that the infrared thermography method can be effective in the detection of defects in very thin multilayer composite structures. As shown by the obtained results, both the selection of the test method and its parameters (*e.g.* heat flux, heating time, generation frequency of thermal stimulation, etc.) are important. The methods of data processing may also have an important role in the detection of defects. This is especially the case when the temperature change on the surface of the sample is small and the noise level is high.

Future work will be directed at improving the efficiency of the methods described in this paper, by developing a methodology for optimizing the parameters of these methods in the examination of specific composites, and selection of the most effective methods of data processing.

Acknowledgment

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References

[1] L. A. Dobrzanski, Non-metallic engineering materials, Wydawnictwo Politechniki Slaskiej, Gliwice, 2008, in Polish
[2] Y.M. Wang, Q. Wu, "Experimental detection of composite delamination damage based on ultrasonic infrared thermography", IJE Transactions B: Applications Vol. 27, No. 11, 2014, pp. 1723-1730
[3] W.F. Cole, M.S. Forte, R.B. Heslehurst,
[4] *Maintainability Issues in ASM Handbook*, Volume 21 – Composites, ASM International, Ohio, 2001, pp. 914-921
[5] X. P. V. Maldague, Theory and practice of infrared technology for nondestructive testing, John Wiley&Sons, Inc. New York, 2001, p. 78.
[6] K. Dragan, W. Świderski, "Multimode NDE approach for structure health assessment of composite elements in aerospace applications" Acta Physica Polonica A, Vol.117, 2010, pp. 878-883.
[7] C. Ibarra-Castanedo, P. Nicolas, E. Grinzato, P. G. Bison, S. Marinetti, C. Cochior-Plescanu, A. H. Bendada, X. Maldague, "Delamination detection and impact damage assessment of GLARE by active thermography", International Journal of Materials&Product Technology, Vol. 41, 2011, pp. 5-16.
[8] J. W. Maclachlan-Spicer, W. D. Kerns, L. Aamodt, J. C. Murphy, "Time-resolved infrared radiometry (TRIR) of multilayer organic coatings using surface and subsurface heating", Proc. SPIE, Vol. 1467, 1991, pp. 311-321.
[9] D. Wu, G. Busse, "Lock-in thermography for nondestructive evaluation of materials" Revue Generale de Thermique, Vol. 37, No 8, 1998, pp. 693-703.
[10] W. Swiderski W., „Lock-in Thermography to rapid evaluation of destruction area in composite materials used in military applications" Proc. SPIE, Vol. 5132, 2003, pp. 506-517.
[11] W. Swiderski, V. Vavilov, "Ultrasonic IR thermographic inspection of graphite epoxy composite: a comparative study of piezoelectric and magnetostrictive stimulation", Opto-Electronics Review, Vol. 23(1), 2015, pp. 33–36.
[12] W. Swiderski W, "Detecting defects in marine structures by using eddy current infrared thermography", Applied Optics, Vol. 55, No. 34, 2016, pp. D17-D21
[13] L. Cheng, G. Y. Tian, "Surface Crack Detection for Carbon Fiber Reinforced Plastic (CFRP) Materials Using Pulsed Eddy Current Thermography", Sensors Journal, No. 11, 2012, pp. 3261-3268.