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DETECTION OF VERY THIN DEFECTS IN CFRP BY THE LOCK-IN THERMOGRAPHY METHOD

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Abstract

Quick development of constructional composite materials application is caused by their excellent mechanical and strength-related properties, combined with a low specific weight. One of the basic groups of reinforcement materials in composites are carbon fibres discovered back in 19th century. The main reason of defects in structures of composite materials is the variability of working charges in constructions during the process of using. Existed defects are complicated because of the effects like loss of continuity of reinfused fibres, binder cracks and loss of fibres adhesiveness to binder. Diagnostic methods, which are effective with relation to metals became little effective when used in detection of defects in composite materials. This caused greater interest of diagnostic techniques with using infrared thermography. Lock-in thermography is one of NDT methods providing phase images of thermal waves in a sample leading to receiving a distribution of internal defects and allowing for thermal properties evaluation. We used lock-in thermography in connection with modulated thermal source synchronized with the IR image acquisition camera. It was prepared sample of multilayer structure carbon composite 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 searches. The results are reported in the paper.

Keywords: *non-destructive testing, composite material, IR thermography*

1. Introduction

Interest composites results from their two basic advantages: firstly their excellent performance and mechanical strength, and secondly their low density. With the simultaneous "combination" of these qualities, typically seen only in the case of composites, their use in those objects in which this combination is of primary importance has rapidly increased in recent years. These objects are mainly aerospace structures, automobiles, sports equipment (boats, skis, tennis rackets, and bicycles) or items used in the armaments industry (minimizing the weight of tanks and armoured vehicles). Composite materials have enabled great progress in these areas, while also increasing the safety of users of this equipment.

The emergence and development of new composite materials was associated with the development of the technology of artificial fibres. The beginning of their development coincided with the period of the Second World War, when glass fibres were widely produced. Further development was related to carbon fibres arising in the 1950s. The next stage in the development of composites led to the appearance of aramid fibres, known by the trade name Kevlar.

Composites reinforced with fibres now dominate the market for composite materials. The fibres used to produce them may be continuous or discontinuous; the latter can be formed short or produced by cutting. The volume fraction of fibres in the composites can be up to 90%. The composites of this type of load carried by the fibre.

A specific group of modern materials are composite materials reinforced with long fibres. In these materials, the reinforcing phase is responsible for load transfer. Therefore, the high strength of this class of materials requires using particularly strong fibres in the preparation process; their arrangement, mutual orientation, and the strength of the bond between fibre and warp, are all-important factors.

Laminar composite materials, which are one of the most frequently used structural composite materials, are composed of several interconnected layers of two-dimensional plates or panels with highly isotropic properties. The individual layers are stacked and mutually connected. Composite laminated materials may also be prepared by using fabrics, including knitted fabrics.

Carbon fibres are used everywhere where the high performance and quality of the final product are more important than the cost. The strength of carbon fibres is connected directly to the covalent bonds between the carbon atoms in their structure. These are some of the strongest bonds, which form between atoms [9]. Carbon fibres have excellent mechanical properties, high chemical resistance, and good thermal stability [4]. Carbon fibres have a much greater strength than glass fibres. Initiation of the destruction of composites based on carbon fibres occurs only with very large forces. Their advantage is particularly evident with regard to composite products that have to operate in wet conditions and under varying loads [5].

The fatigue strength of composites is one of the most important problems in the operation of composite structures. Given the complexity of the mechanisms responsible for fatigue weakening of composite materials, anticipating their time of failure at the current state of the art is virtually impossible. This forces constant monitoring of these components, which in turn affects the development of non-destructive testing techniques for such materials. The basic mechanism of destruction of composite materials is cracking. Typically, this process is initiated in the immediate vicinity of material defects, such as areas in which the homogeneity of the matrix material is reduced (i.e., voids) or other areas of stress intensification. One of the methods that are effective in the non-destructive testing of composites is infrared thermography.

2. Lock-in thermography

Lock-in thermography is one of the main methods of thermography with regard to which research is currently active. The principle of operation of lock-in thermography is based on the creation of a thermal wave on the surface of the object through its periodic thermal loading. This wave moves into the object and with distance from the surface is absorbed and causes a negative phase shift. When the wave reaches the area in the material where there are any thermo-physical changes (e.g., delamination or inclusions), it is partly reflected. The reflected portion of thermal wave constitutes an obstacle to a wave formed on the surface, giving an interference pattern in the local surface temperature, thus causing the radially outer surface to oscillate at a particular frequency, in response to the waves' heating. Calculating the amplitude and phase of the temperature on the surface gives information about the internal structure of the object. Interference images are analysed by special algorithms. These algorithms can be used not only when a material has a thickness substantially corresponding to the length of the thermal wave, but also detect the actual differences in the thermophysical properties of the structure.

Thermal waves on the surface of an object undergoing testing are not only reflected by its internal structure. Some of parameters of the object, for example its porosity, have an influence on the time behaviour of local temperature fluctuations. This makes it possible to compare each object with respect to any changes of properties. The important advantage of lock-in thermography is that a periodic excitation test may be performed at relatively low energy, which is absorbed by the object. It allows for the testing of thermally sensitive components, and the use of relatively simple energy sources.

There are four main variations of the lock-in thermography method:

– Standard method, which can be called "classic", based on repeated multiplication of the recorded signal response of the object *s(t)* to thermal force, with the reference signal (phase p_f and q_f quadrature) shifted by 90° relative to the excitation [3]. The amplitude A and phase φ included in the signal *s (t)* of frequency *f* are calculated using the following formulas:

$$tg(\varphi - \varphi_r) = \frac{SQ_f}{SP_f}, \qquad A = \frac{2}{N}\sqrt{SP_f^2 + SQ_f^2}\ , \tag{1}$$

where:

$$SP_f = \sum_{i=1}^{N} s(t_i) p_f(t_i), \qquad SQ_f = \sum_{i=1}^{N} s(t_i) q_f(t_i), \tag{2}$$

$$p_f(t) = \sin(2\pi f t + \varphi_r), \qquad q_f(t) = \cos(2\pi f t + \varphi_r). \tag{3}$$

– Four-point method [5, 6], in which a thermal wave in the form of a sinusoidal is excited by a heating lamp or ultrasound [6]. Four thermal images (thermograms) are recorded during one cycle, which correspond exactly to the next phase-shifted by 90° (Fig. 1). The triggering of the infrared camera is synchronized with the source of stimulation. The algorithm used for the calculations is a Fourier transform of the time-dependent amplitude of each point of a thermogram.

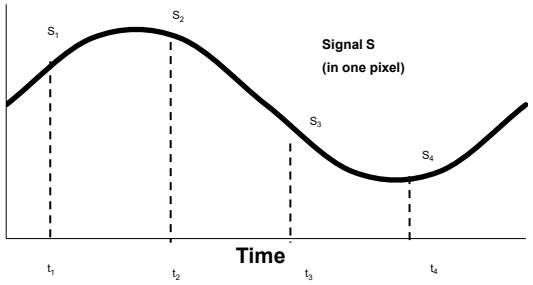

Fig. 1. Signal acquisition during thermal wave cycle

Phase and amplitude are calculated for each pixel in accordance with the following formula [8]:

$$\varphi = \arctan\left(\frac{S_1 - S_3}{S_2 - S_4}\right), \tag{4}$$

$$A = \sqrt{[S_1 - S_3]^2 + [S_2 - S_4]^2}. \tag{5}$$

The image of the angle of the phase shift (phase image) represents the delay between stimulating the flow of heat and the temperature field generated in response to this stimulation. It is known that the phase image carries more information about the object's structure than the amplitude image. The phase image is also less sensitive to changes in emissivity, uneven heating of the sample and local temperature changes.

– Variational method [7] is based on the use of statistical analysis. That does not require a synchronizing signal. However, it only provides information about the amplitude of the signal. Assuming that the interference of the measuring apparatus and the useful signal are random, and that the thermal excitation signal is sinusoidal, the amplitude can be determined from the formula:

$$A = \sqrt{2(V_s - V_b)}, \tag{6}$$

where:

V_s – variation of experimental signal;

V_b – variation of the noise.

– The least squares method [2], in which both the amplitude and phase shift of the response signal are determined from the minimum mean square error between the measured and theoretical signal. Phase and amplitude are calculated from the formula:

$$tg\Delta\varphi = \frac{\overline{SQ_f}(\overline{N} - \overline{Q_{2f}}) - \overline{SP_f P_{2f}}}{\overline{SP_f}(\overline{N} + \overline{Q_{2f}}) - \overline{SQ_f P_{2f}}}, \tag{7}$$

$$A = 2\frac{\overline{SP_f}\cos\Delta\varphi + \overline{SQ_f}\sin\Delta\varphi}{\overline{N} - \overline{Q_{2f}}\cos 2\Delta\varphi + \overline{P_{2f}}\sin 2\Delta\varphi}, \tag{8}$$

where:

P_{2f} and Q_{2f} – refers to the double pulse reference function.

$$\overline{SP_f} = SP_f - P_f S/N \qquad \overline{SQ_f} = SQ_f - Q_f S/N, \tag{9}$$

$$\overline{P_{2f}} = P_{2f} - 2P_f Q_f/N \qquad \overline{Q_{2f}} = Q_{2f} + (P_f^2 - Q_f^2)/N, \tag{10}$$

$$\overline{N} = N - (P_f^2 + Q_f^2)/N. \tag{11}$$

3. Experimental testing

The set-up for experimental testing with the lock-in thermography method (four-point method) is presented in Fig. 2. 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 a sinusoidal form of thermal wave at a specific frequency [1, 10].

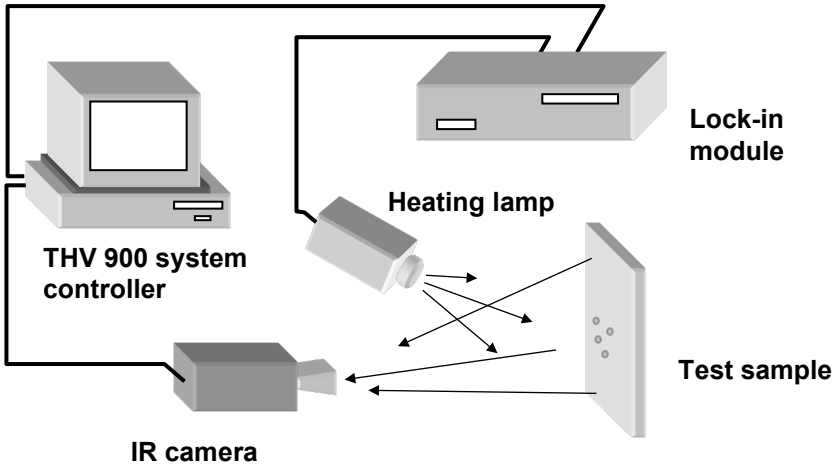

Fig. 2. Experimental set-up

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

The test sample (Fig. 3) was made of two plates of carbon fibre (150x350 mm), having a thickness of 1 mm, connected to a layer of epoxy resin, having a thickness of approx. 0.1 mm. Six defects were placed between the plates, three of copper sheet (squares having a side of 20 and 10 mm and a circle having a diameter of 20 mm) and three of Teflon of the same size and shape.

Figure 4 shows the phase and amplitude images made by the lock-in thermography method at a frequency of 0.06 Hz from part of the sample (Fig. 3), on which are shown four sub-surface defects. Two of these (number 1) are made of copper sheet (10x10 mm and 20x20 mm) and the two Teflon defects (20x20 and a circle having a diameter of 20 mm) seen on the amplitude image and marked with number 2.

Fig. 3. The test sample

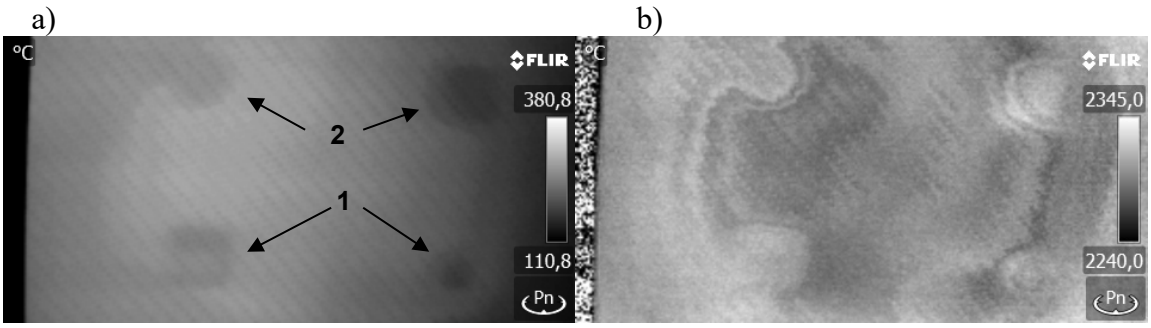

Fig. 4. The results of analysis by lock-in at a frequency of 0.06 Hz a) amplitude image b) phase image

Phase and amplitude images of other parts of the sample, on which can be seen the other two defects marked with number 3, are shown in Fig. 5.

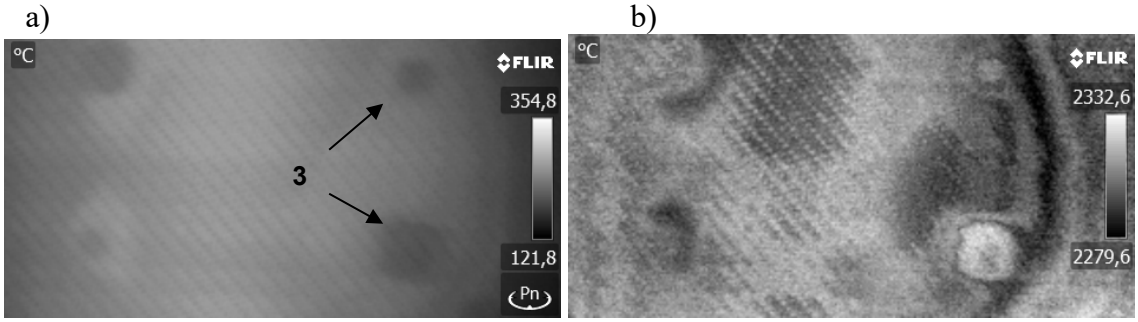

Fig. 5. The results of analysis by lock-in at a frequency of 0.06 Hz a) amplitude image b) phase image

For comparison, research was conducted on the sample by using a lock-in measuring set of the Automation Technology Company. Measurements were recorded with a FLIR SC 7600 camera. There is no known description of the algorithm. The type of lock-in technique method that uses this arrangement. Fig. 6 shows an amplitude image of the same defects, also visible in Fig. 4.

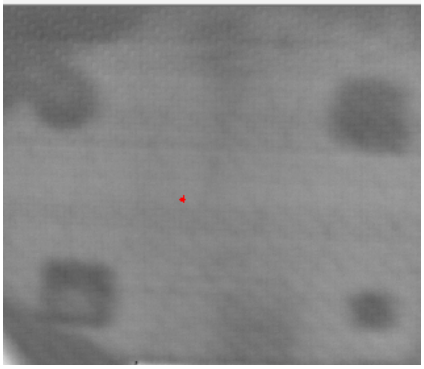

Fig. 6. Phase image

4. Conclusions

As is apparent from obtained results, the lock-in thermography method can be effective for detecting thin defects in carbon fibre reinforced plastic. This is essential for defects such as delamination, which are among the most common defects in this type of material.
As demonstrated by the performed tests, the choice of an appropriate frequency is more significant for the detection of defects than is the resolution of the thermal camera used in the tests. The results presented in this paper show important role of frequency in the detection of defects.

Future work will focus on comparative tests using other methods of active infrared thermography, to determine which of them may be the most effective non-destructive testing method for such materials.

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